ERDC/CHL TR-02-7

Coastal and Hydraulics Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

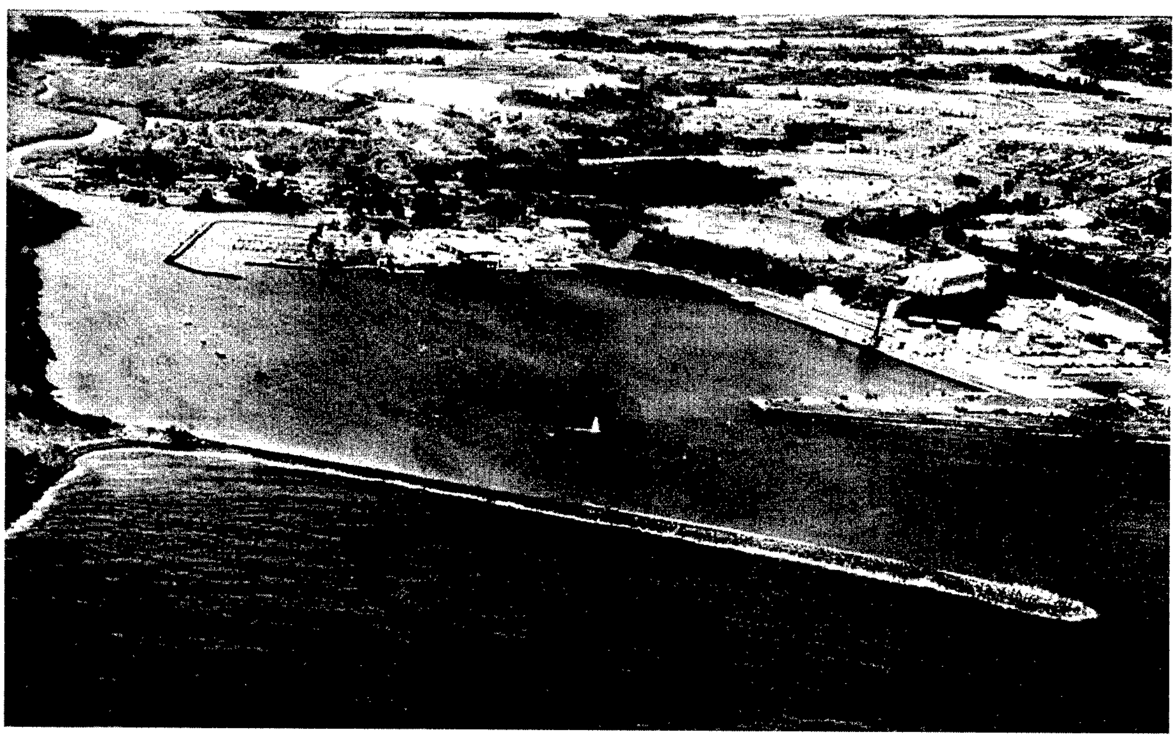
Monitoring Completed Navigation Projects Program

Periodic Inspection of Nawiliwili Harbor Breakwater, Kauai, Hawaii

Armor Unit Monitoring for Period 1995-2001

Robert R. Bottin, Jr., and Daniel T. Meyers

June 2002



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Periodic Inspection of Nawiliwili Harbor Breakwater, Kauai, Hawaii

by Robert R. Bottin, Jr.

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Final report

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

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Preface

The study reported herein was conducted as part of the Monitoring Completed Navigation Projects (MCNP) Program, formerly Monitoring Completed Coastal Projects Program. Work was conducted under Work Unit IM-7, "Periodic Inspections." Overall program management for MCNP is administered by Headquarters, U.S. Army Corps of Engineers (HQUSACE). The Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC) is responsible for technical as well as data management and support for HQUSACE review and technology transfer. Technical Monitors for the MCNP Program are Messrs. Barry W. Holliday, Charles B. Chesnutt, and David B. Wingerd (HQUSACE). The Program Manager is Mr. Robert R. Bottin, Jr., (CHL).

This report is part of a series which tracks the long-term structural response of the Nawiliwili Harbor Breakwater, HI, to its environment. Limited ground surveys, aerial photography, and photogrammetric analysis of the breakwater were conducted by Richard B. Davis, Inc., Smith River, CA, and David C. Smith and Associates, Inc., Portland, OR, under contract to the U.S. Army Corps of Engineers. A broken armor unit survey was conducted by Messrs. Bottin, Hugh F. Acuff, Larry R. Tolliver, Glenn B. Myrick, Ms. Kristi Evans (CHL), and Mr. Daniel T. Meyers, U.S. Army Engineer District, Honolulu (CEPOH).

The work was conducted during the period August through October 2001 under the general supervision of Mr. Thomas W. Richardson, Director, CHL, and Mr. Thomas J. Pokrefke, Jr., Acting Assistant Director, CHL, and under direct supervision of Mr. Dennis G. Markle, Chief, Coastal Harbors and Structures Branch. This report was prepared by Messrs. Bottin, CHL, and Meyers, CEPOH.

At the time of publication of this report Dr. James R. Houston was Director of ERDC, and COL John W. Morris III was Commander and Executive Director.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in figures, plates, and tables of this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic yards	0.7646	cubic meters
degrees (angle)	0.01745329	radians
feet	30.48	centimeters
feet	0.3048	meters
inches	25.4	millimeters
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

Monitoring Completed Navigation Projects Program

The goal of the Monitoring Completed Navigation Projects (MCNP) Program (formerly the Monitoring Completed Coastal Projects Program) is the advancement of coastal and hydraulic engineering technology. The program is designed to determine how well projects are accomplishing their purposes and are resisting the attacks by their physical environment. These determinations, combined with concepts and understanding already available, will lead to creating more accurate and economical engineering solutions to coastal and hydraulic problems; to strengthening and improving design criteria and methodology; to improving construction practices and cost-effectiveness; and to improving operations and maintenance techniques.

To develop direction for the program, the U.S. Army Corps of Engineers initially established an ad hoc committee of engineers and scientists. The committee formulated the objectives of the program, developed its operation philosophy, recommended funding levels, and established criteria and procedures for project selection. A significant result of their efforts was a prioritized listing of problem areas to be addressed, essentially a listing of the areas of interest of the program.

Corps offices are invited to nominate projects for inclusion in the monitoring program as funds become available. The MCNP Program is governed by Engineer Regulation 1110-2-8151 (Headquarters, U.S. Army Corps of Engineers (HQUSACE) 1997). A selection committee reviews and prioritizes the projects nominated based on criteria established in the regulation. The prioritized list is reviewed by the Program Monitors at HQUSACE. Final selection is based on this prioritized list, national priorities, and the availability of funding.

The overall monitoring program is under the management of the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC), with guidance from HQUSACE. Development of monitoring plans and the conduct of data collection and analyses are dependent upon the combined resources of CHL and the District/Division. The inspection for the study reported herein, was completed as part of the "Periodic Inspections" work unit of the MCNP Program.

Work Unit Objective and Monitoring Approach

The objective of the "Periodic Inspections" work unit in the MCNP Program is to monitor selected coastal navigation structures periodically to gain an understanding of the long-term structural response of unique structures to their environment. These periodic data sets are used to improve knowledge in design, construction, and maintenance of both existing and proposed coastal navigation projects. These data also will help avoid repeating past design mistakes that have resulted in structure failure and/or high maintenance costs. Past projects monitored under the MCNP Program and/or structures with unique design features that may have application at other sites are considered for inclusion in the periodic inspections monitoring program. Selected sites are presented as candidates for development of a periodic monitoring plan. Once the monitoring plan for a site is approved and funds are provided, monitoring of the site is initiated. Normally, base conditions are established and documented in the initial effort. The site then is reinspected periodically (frequency of surveys is based on a balance of need and funding for each monitoring site) to obtain long-term structural performance data.

Low-cost remote sensing tools and techniques, with limited ground truthing surveys, are the primary inspection tools used in the monitoring efforts. Most periodic inspections consist of capturing above-water conditions of the structure at periodic intervals using high-resolution aerial photography. Periodic aerial photographs are compared visually to gauge the degree of in-depth analysis required to quantify structural changes (primarily armor unit movement). Data analysis involves using photogrammetric techniques developed for and successfully applied at other coastal sites. At sites where local wave data are being gathered by other projects and/or agencies, and these data can be acquired at a relatively low cost, wave data are correlated with structural changes. In areas where these data are not available, general observations and/or documentation of major storms occurring in the locality are presented along with the monitoring data. Ground surveys are limited to the level needed to establish accuracy of the photogrammetric techniques.

When a coastal structure is photographed at low tide, an accurate permanent record of all visible armor units is obtained. Through the use of stereoscopic, photogrammetric instruments in conjunction with photographs, details of structure geometry can be defined at a point in time. By direct comparison of photographs taken at different times, as well as the photogrammetric data resolved from each set of photographs, geometric changes (i.e., armor unit movement and/or breakage) of the structure can be defined as a function of time. Thus, periodic inspections of the structures will capture permanent data that can be compared and analyzed to determine if structure changes are occurring that indicate possible failure modes and the need to monitor the structure(s) more closely. The Nawiliwili Harbor breakwater, Kauai, HI, was nominated for periodic monitoring by the U.S. Army Engineer District, Honolulu. Initial monitoring of base level conditions was completed in 1995 (Bottin and Boc 1996).

Three additional Honolulu District projects have been monitored previously under the "Periodic Inspections" work unit. Base conditions have been defined

for the Kahului Harbor, Maui, HI, Laupahoehoe boat launching facility, HI, breakwaters (Markle and Boc 1994), and Ofu Harbor breakwater, American Samoa (Bottin and Boc 1997).

Project Location and Brief History

Nawiliwili Harbor is located on the southeast coast of the island of Kauai (Figure 1) approximately 185 km (115 miles)[1] northwest of Honolulu, Oahu, HI. The harbor is protected by a 625-m-long (2,050-ft-long) rubble-mound breakwater. The Nawiliwili breakwater protects the inner breakwater of the small-boat harbor, the commercial harbor, and major industries along its waterfront (Figure 2). An aerial view of the harbor is shown in Figure 3. The breakwater is one of the most complex rubble-mound structures the Corps has constructed. It was originally armored with keyed-and-fitted stone, and now has several sizes of dolos and tribar concrete armor units. The structure has a unique rib cap that provides buttressing for the armor and access along its alignment. It has had a long history of repair since its original construction was completed in 1922. The breakwater has repeatedly been subjected to major storm events, including three hurricanes during its 80-year history.

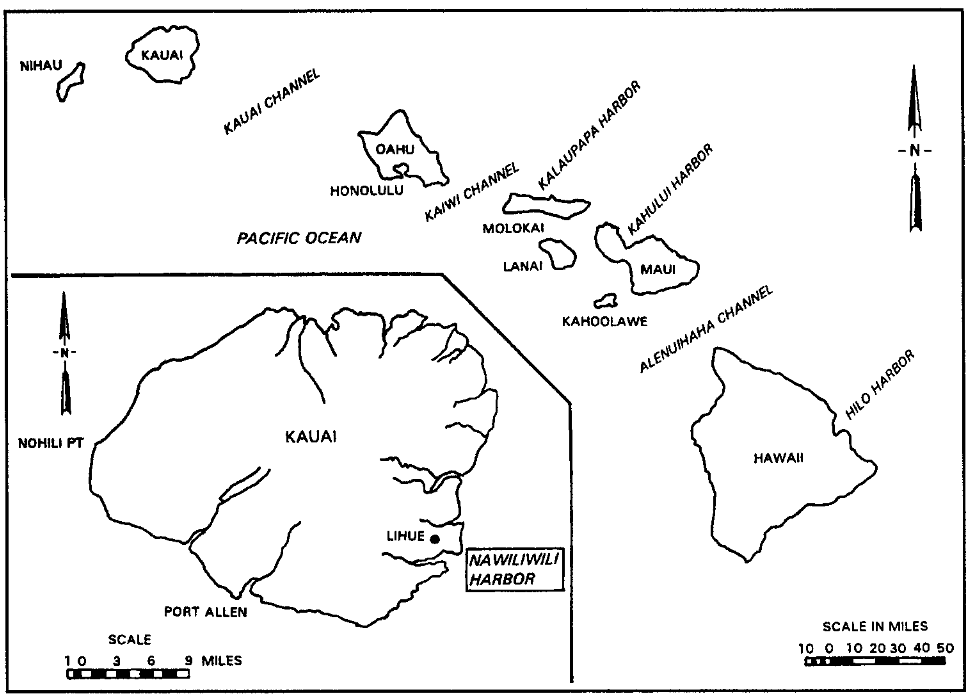

Figure 1. Project location

[1] Units of measurement in the text of this report are shown in SI units, followed by non-SI units in parenthesis. In addition, a table of factors for converting non-SI units of measurement used in figures in this report to SI units is presented on page vi.

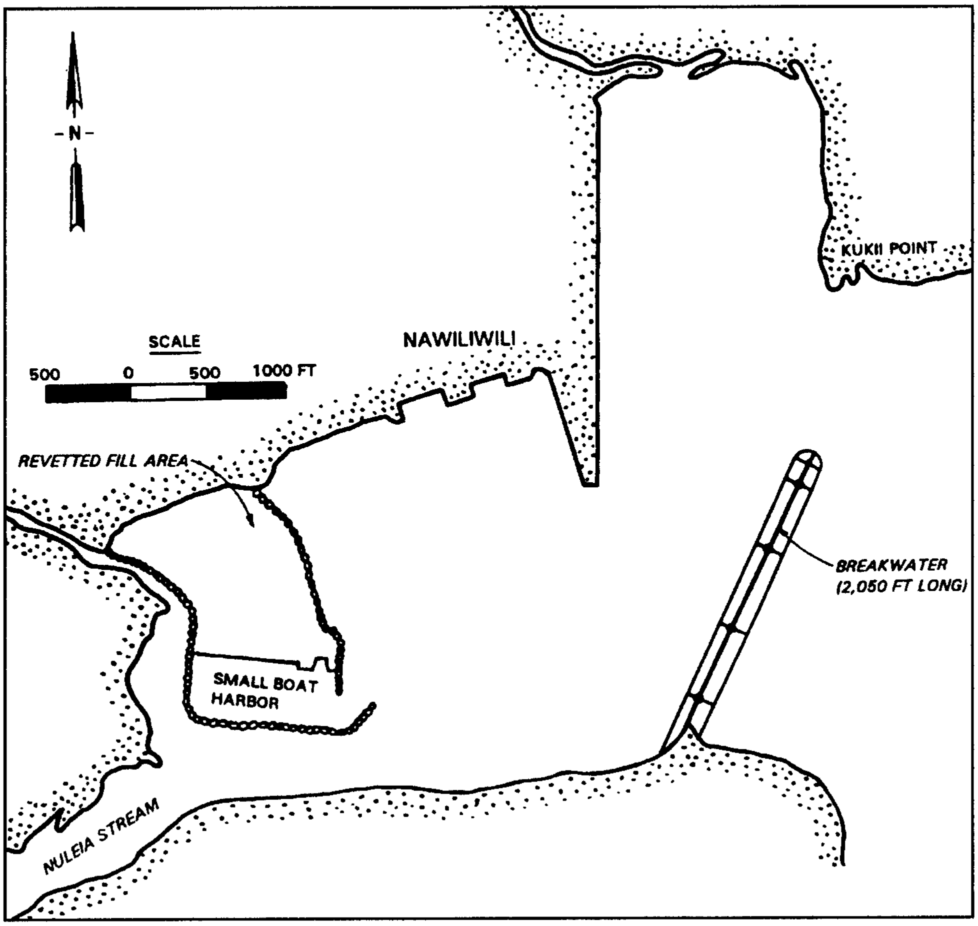

Figure 2. Layout of Nawiliwili Harbor, HI

Figure 3. Aerial view of harbor (2001)

The breakwater was originally constructed with a single layer of keyed and fitted armor stone placed over quarryrun core stone (227 kg (500 lb) or less). The armor cover on the breakwater consisted of 9,070-kg (10-ton) stone on the crest

and sea-side slope to an elevation (el) of -0.9 m (-3 ft)[1], 1,814-kg (2-ton) stone on the harbor-side slope from the crest to an el of –0.9 m (-3 ft), and 454-kg (0.5-ton) stone on both the sea-side and harbor-side slopes from the -0.9 m (-3 ft) el to the existing bottom. The breakwater was constructed with a 1V:1H slope on the harbor side and a 1V:1.5 slope on the sea side from the crest to an el of -3.7 m (-12 ft). Below the -3.7 m (-12 ft) el, the sea-side slope was 1V:1H to the existing bottom (Sargent, Markle, and Grace 1988). The breakwater had a 4.6-m (15-ft) crest width with an el of +3.4 m (+11 ft). A cross section of the original structure is shown in Figure 4.

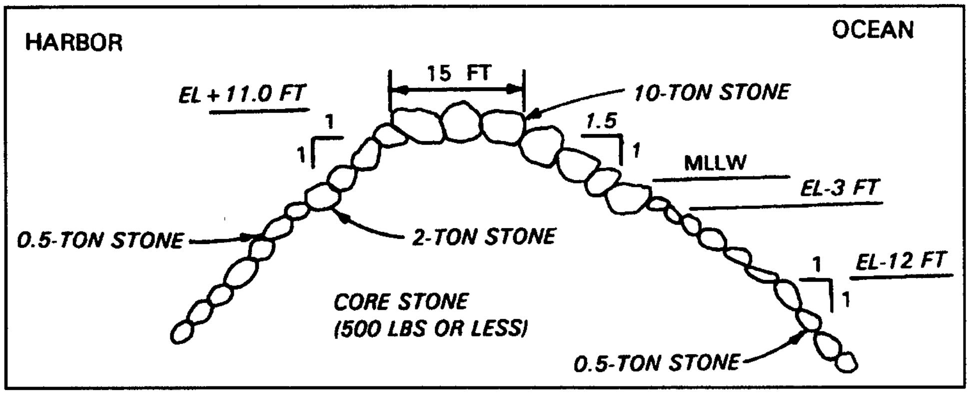

Figure 4. Typical cross section of originally constructed breakwater

The first major storm damage occurred in 1929, and the slope of the structure was repaired by resetting 114 stones and adding 2,857,600 kg (3,150 tons) of stone and concrete blocks. Between 1930 and 1952, an additional 1,814,370 kg (2,000 tons) of stone were used in repair work on the structure. In 1954, the breakwater again experienced severe storm damage. The head section and approximately 30.5 m (100 ft) of the trunk were destroyed. Severe storms again impacted the breakwater in 1956 and an additional 100-m (330-ft) section of trunk was destroyed. The storms of 1954 and 1956, and yet another in 1957, led to the first major rehabilitation of the structure in 1959 (Turk, Melby, and Young 1995).

The 1959 rehabilitation utilized 16,150-kg (17.8-ton) tribar armor units. A two-layer, random placement was used on the head and outer 15.2 m (50 ft) of the structure, and uniformly placed, single layer placement was used along 152 m (500 ft) of trunk on the sea-side slope (stas 15+00 - 20+00). A concrete cap also was poured on the crest of the breakwater in 1959 with a crest el of +4.0 m (+13 ft). Typical cross sections for the 1959 repair are shown in Figure 5. The wave height used for design of the armor units for the 1959 rehabilitation was 7.3 m (24 ft). Of the 598 tribars placed, 351 were reinforced. The Corps tagged 150 of the tribars for indicators of movement on the slope during future surveys. After the rehabilitation was completed, Hurricane Dot struck Kauai. It was reported that the structure survived with only minor damage. Three tribars were broken, and

[1]All elevations (el) and depths cited herein are in meters (feet) referred to mean lower low water (mllw).

some shifting of armor units occurred. Wave heights were estimated as approaching the 7.3-m (24-ft) design wave height.

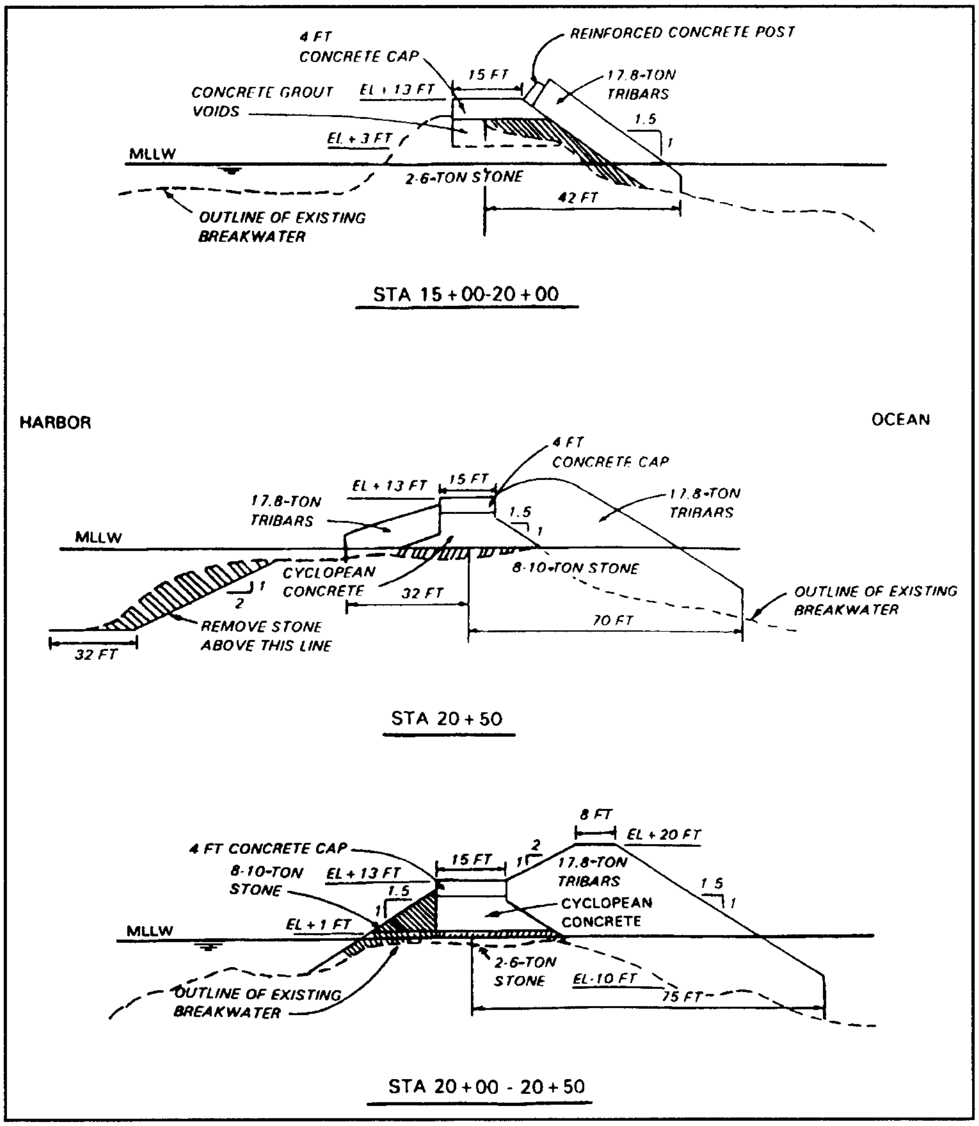

Figure 5. Typical cross sections for 1959 breakwater repairs

Due to continued damage to the breakwater, another rehabilitation was initiated in 1977. It consisted of the use of 9,980-kg (11-ton) dolos armor units. Two layers of unreinforced dolosse (485 units) were placed from the toe to approximately +1.5 m (+5.0 ft) over the one-layer tribar trunk section (stas 15+00 - 20+00). In addition, two layers of dolosse (449 units) were placed from the toe to the crest on the sea-side slope of the trunk for a distance of 91 m (300 ft) shoreward of the tribar area (stas 12+00 - 15+00). Model testing (Davidson 1978) found the dolosse to be hydraulically stable. The sea-side slope shoreward of the dolosse (sta 5+00 - 12+00) also was repaired with 6,350-10,890-kg (7-12-ton) stone during the rehabilitation. Cross sections of the 1977 repairs are shown in Figure 6. A breakwater survey conducted in 1980 indicated that the breakwater was in good condition with minimal armor unit breakage observed.

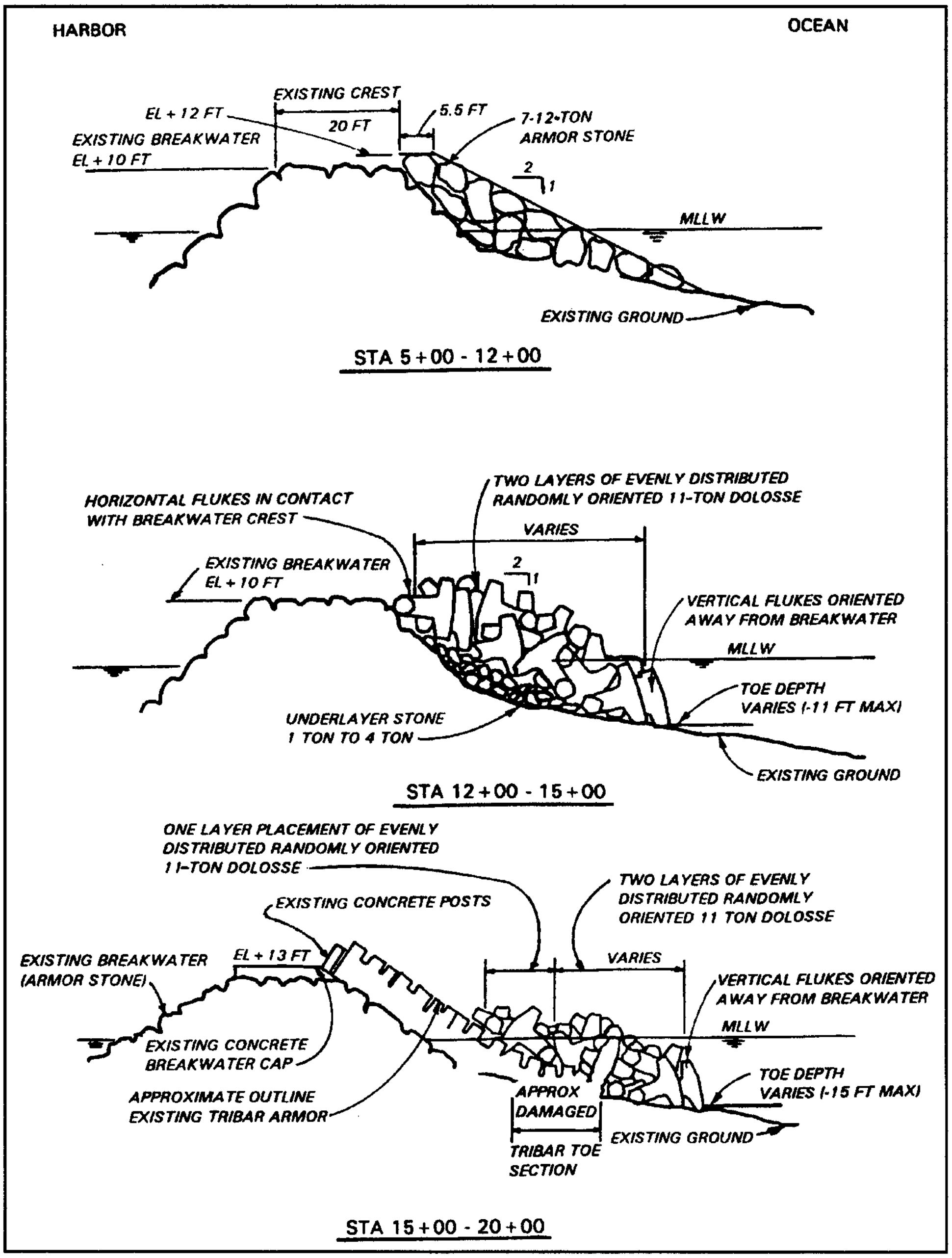

Figure 6. Typical cross sections for 1977 breakwater repairs

Kauai was devastated by Hurricane Iwa in 1982. Large waves were reported, and a subsequent inspection revealed nine dolosse and one tribar broken. Movement and shifting of stones on the crest of the structure were noted. A detailed underwater inspection in 1983 found the slope at the structure's head to be approximately 1V:1H, much steeper than the design slope.

In 1987, the breakwater was rehabilitated with 20,865-kg (23-ton) reinforced dolosse (230 units). These units were placed along the steepened head section below the water surface and randomly in low areas around the existing head above the waterline. On the harbor-side slope, one layer of 5,900-kg (6.5-ton) tribars was placed along a portion of deteriorated trunk (stas 12+00 - 15+00). This

design was model tested (Markle and Herrington 1983), and it was determined that it provided adequate stability. In addition, a 260-m-long (850-ft-long) concrete rib cap was constructed (stas 12+00 - 20+50) to buttress the concrete armor units. Cross sections of the 1987 repairs are shown in Figure 7.

Hurricane Iniki struck the island of Kauai in 1992 with Nawiliwili almost directly in its path. Eyewitness accounts indicated that seas outside the harbor reached 10 m (33 ft) during the storm and over 3 m (10 ft) inside the harbor. Storm surge exceeded 5 m (16 ft) along much of the southern island coast. A survey revealed that three 20,865-kg (23-ton) dolosse, seven 9,980-kg (11-ton) dolosse, and six 16,150-kg (17.8-ton) tribars had broken as a result of the hurricane. A survey of the structure in 1994 revealed a total of 54 broken concrete armor units on the structure above the water line.

Prior Monitoring (Periodic Inspection) of Site

Initial monitoring of the Nawiliwili breakwater was completed in October 1995 as part of the "Periodic Inspections" work unit of the MCNP Program (Bottin and Boc 1996). Work included armor unit targeting, limited ground surveys, aerial photography, photogrammetric analyses of armor units, and a broken armor unit survey. The information obtained during the monitoring effort established base level conditions for the breakwater. Precise positions of targeted armor units were obtained as well as centroid data and orientations of the targeted armor units. The broken armor unit survey revealed that 70 broken/cracked armor units existed on the structure. An aerial photo of the Nawiliwili breakwater in 1995 is shown in Figure 8.

Purpose of Current Monitoring

The purposes of the study reported herein were to:

Utilize methodology previously developed using limited land-based surveying, aerial photography, and photogrammetric analysis to assess the long-term stability response of the concrete armor units on the Nawiliwili breakwater.

Conduct limited land surveys, a broken armor unit inspection, aerial photography, and photogrammetric analyses to accurately define armor unit movement above the waterline.

Compare the breakwater's armor unit positions to those obtained during the survey conducted in 1995 and define changes that have occurred.

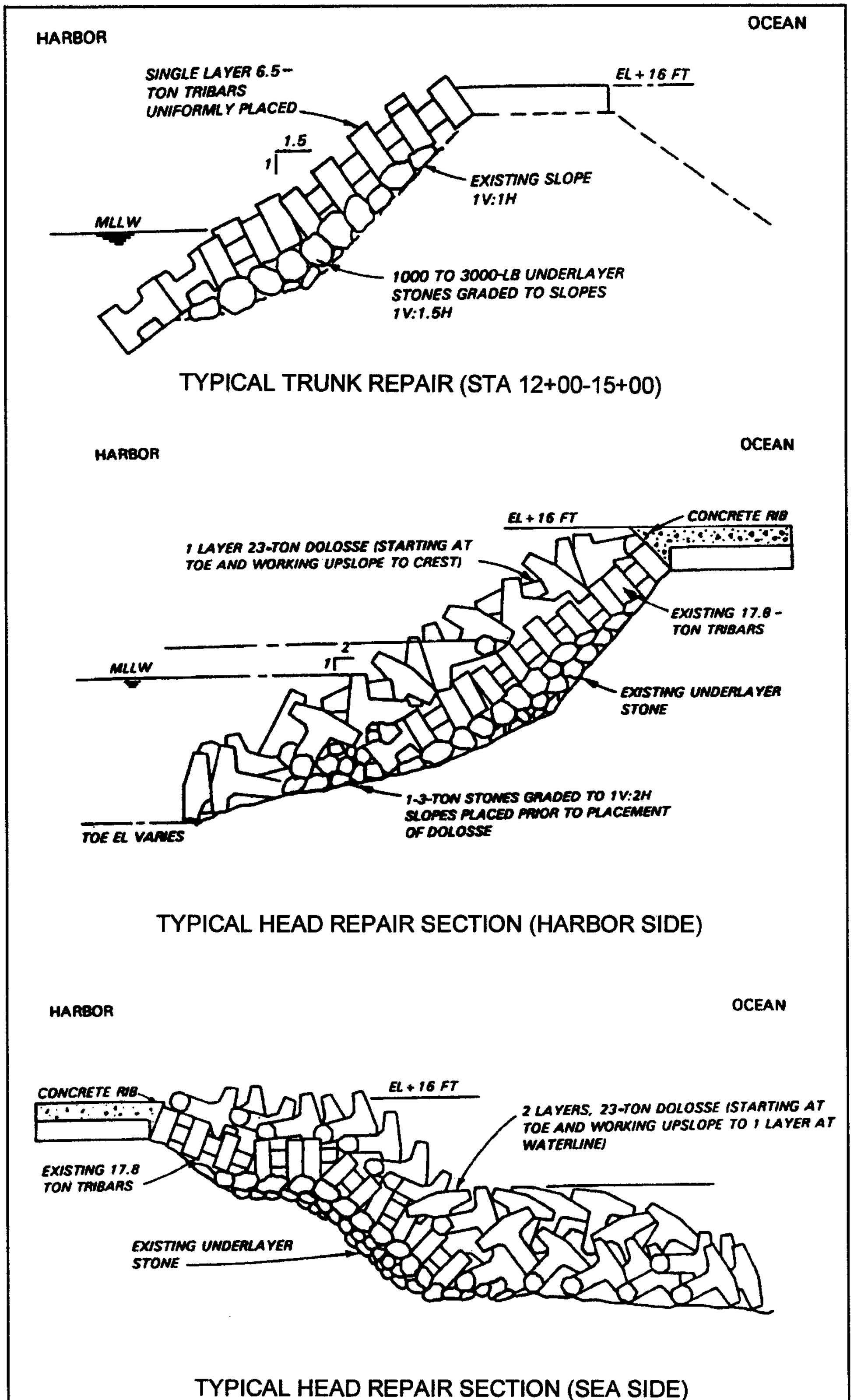

Figure 7. Typical cross sections for 1987 breakwater repairs

Figure 8. Aerial photograph of Nawiliwili breakwater (1995)

2 Monitoring Plan and Data Comparison

The objective of the current monitoring effort in the "Periodic Inspections" work unit was to re-examine the targeted concrete armor units on the outer 260-m-long (850-ft-long) portion of the Nawiliwili breakwater and determine changes that have occurred since the last inspection in 1995. The monitoring plan consisted of targeting armor units, limited ground surveys, aerial photography, photogrammetric analysis of armor unit locations, a ground-based broken armor unit survey, and comparisons of current armor unit positions with those obtained previously.

Targeting and Ground Surveys

To serve as control for the ground-based survey as well as the photogrammetric work, existing monuments from previous surveys were located and re-surveyed using Trimble real-time kinemetic global system positioning system equipment and electronic surveying techniques. Monuments at the site used to establish vertical and horizontal control are shown in Figure 9.

In addition, targets were re-established on selected concrete armor units. A total of 21 armor units was selected for monitoring, 11 along the sea side of the breakwater trunk and 10 around the breakwater head. A description of the targeted units is presented in Table 1. Along the trunk, nine of the targeted units were 9,980-kg (11-ton) dolos, and two were 16,150-kg (17.8-ton) tribars. Around the head, five units were 20,865-kg (23-ton) dolos, and five were 16,150-kg (17.8-ton) tribars. Selected units were distributed along the outer 260-m (850-ft) length of the breakwater and from the crest to the waterline. Dolosse and tribars were chosen roughly in proportion to the relative frequency of each unit along a particular length of breakwater. Units were chosen for targeting that had flat surfaces close to horizontal to maximize their visibility in aerial photography and allow for accurate representation of armor unit movement. Figure 10 shows the locations of targeted armor units on the Nawiliwili Harbor breakwater using an identifier of NA, NB, etc.

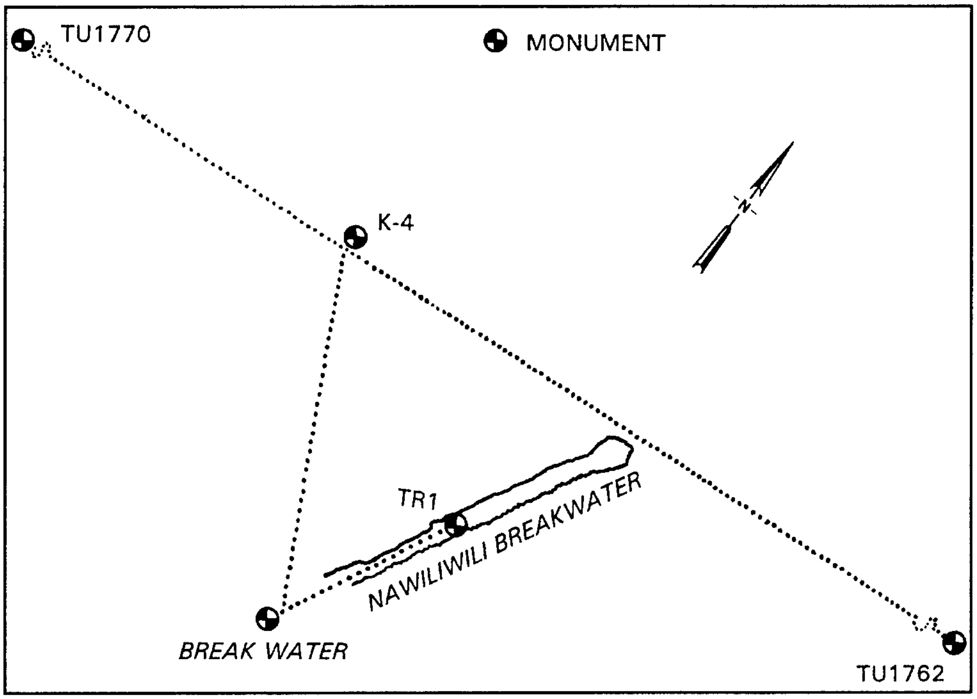

Figure 9. Monuments used to establish survey control

Table 1
Description of Targeted Armor Units

Unit	Description	Unit	Description
NA	9,980-kg (11-ton) Dolos	NM	16,150-kg (17.8-ton) Tribar
NB	9,980-kg (11-ton) Dolos	NN	16,150-kg (17.8-ton) Tribar
NC	16,150-kg (17.8-ton) Tribar	NO	20,865-kg (23-ton) Dolos
ND	9,980-kg (11-ton) Dolos	NP	16,150-kg (17.8-ton) Tribar
NE	9,980-kg (11-ton) Dolos	NQ	16,150-kg (17.8-ton) Tribar
NF	20,865-kg (23-ton) Dolos	NR	9,980-kg (11-ton) Dolos
NG	20,865-kg (23-ton) Dolos	NS	9,980-kg (11-ton) Dolos
NH	20,865-kg (23-ton) Dolos	NT	9,980-kg (11-ton) Dolos
NJ	20,865-kg (23-ton) Dolos	NV	9,980-kg (11-ton) Dolos
NK	16,150-kg (17.8-ton) Tribar	NZ	9,980-kg (11-ton) Dolos
NL	16,150-kg (17.8-ton) Tribar		

Each armor unit selected for targeting was painted with three, 30.5-cm (12-in.) diam targets. The targets were divided into four quadrants that were painted alternately white and black. This style of contrasting target provides a precise center point for which measurements can be made by both land surveys and photogrammetric work. A high quality expoxy-based marine paint was used to minimize the need for repainting, and a 2.54-cm (1-in.) cross was chiseled at the center of each target for identification in subsequent surveys. Each targeted unit was labeled conspicuously with two, 15.2-cm (6-in.) high white letters, the first being "N" for Nawiliwili and the second being an identifying letter for the particular unit. Each target on its repective armor unit was identified with a single 15.2-cm (6-in.) white numeral labeled "1" through "3." Examples of targeted armor units are shown in Figures 11 and 12.

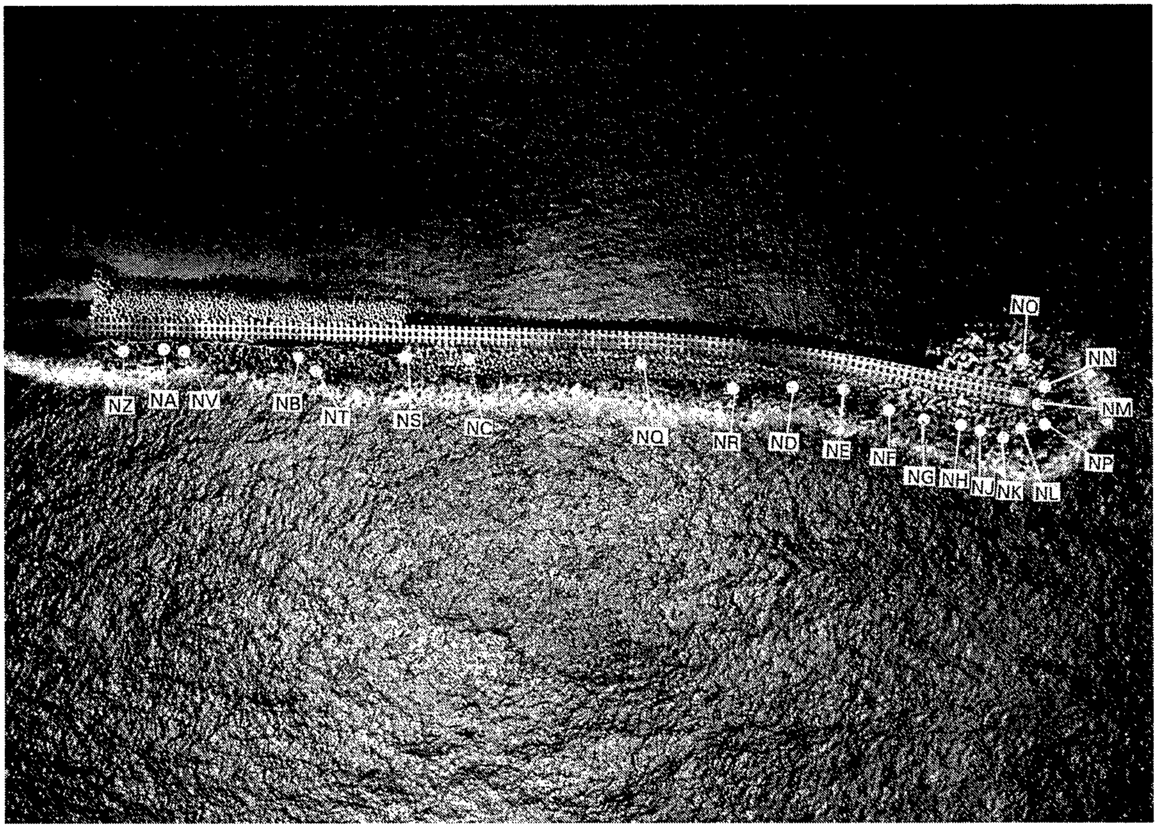

Figure 10. Locations of targeted armor units

Figure 11. Example of a targeted 17.8-ton tribar

Figure 12. Example of a targeted 11-ton dolos

Limited ground surveys of some of the concrete armor unit targets were conducted on 4 August 2001 to serve as control to check the accuracy of the subsequent photogrammetric work. Target coordinates were established using a Wild T-2000 total station surveying instrument. Horizontal positions were based on the Hawaii State Plane Coordinate System, Zone 4, and elevations were referenced to mean lower low water (mllw) datum.

Aerial Photography

Aerial photography is an effective means of capturing images of large areas for later analysis, study, visual comparison to previous or subsequent photography, or measurement and mapping. Its chief attribute is the ability to freeze a moment in time, while capturing extensive detail.

Aerial photography was obtained along the Nawiliwili breakwater with a Zeiss RMK A 15/23 aerial mapping camera (9-in. by 9-in. format). Color photos were secured from a fixed-wing aircraft flying at an appropriate altitude, which resulted in high resolution images and contact prints with scales of 1:1,200. Photographic stereo pairs were obtained during the flights. Stereo pairs secured for the breakwater are shown in Figures 13-15. The aerial photography was obtained on 4 September 2001.

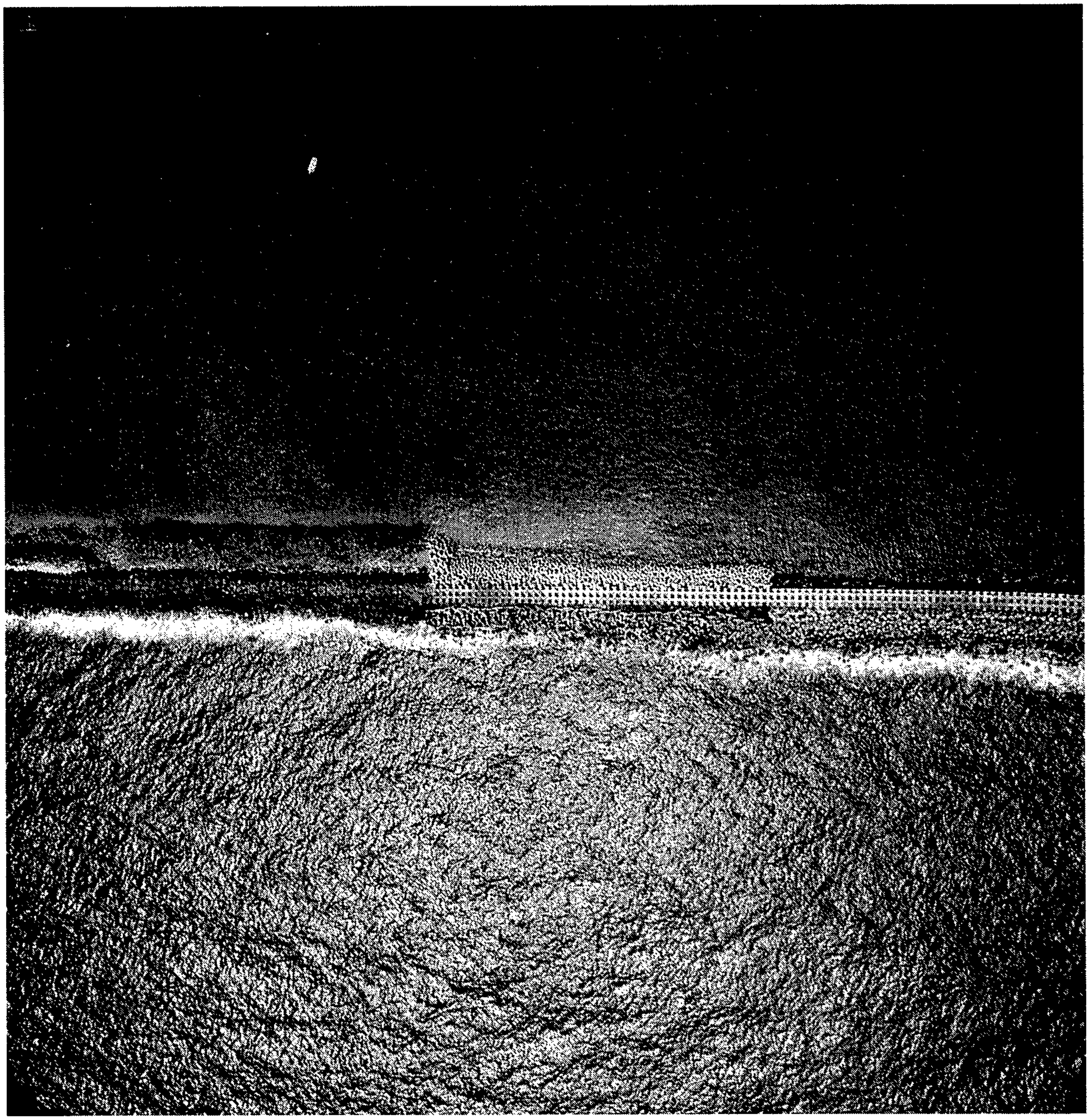

Figure 13. Stereo pair photograph of Nawiliwili breakwater (innermost image)

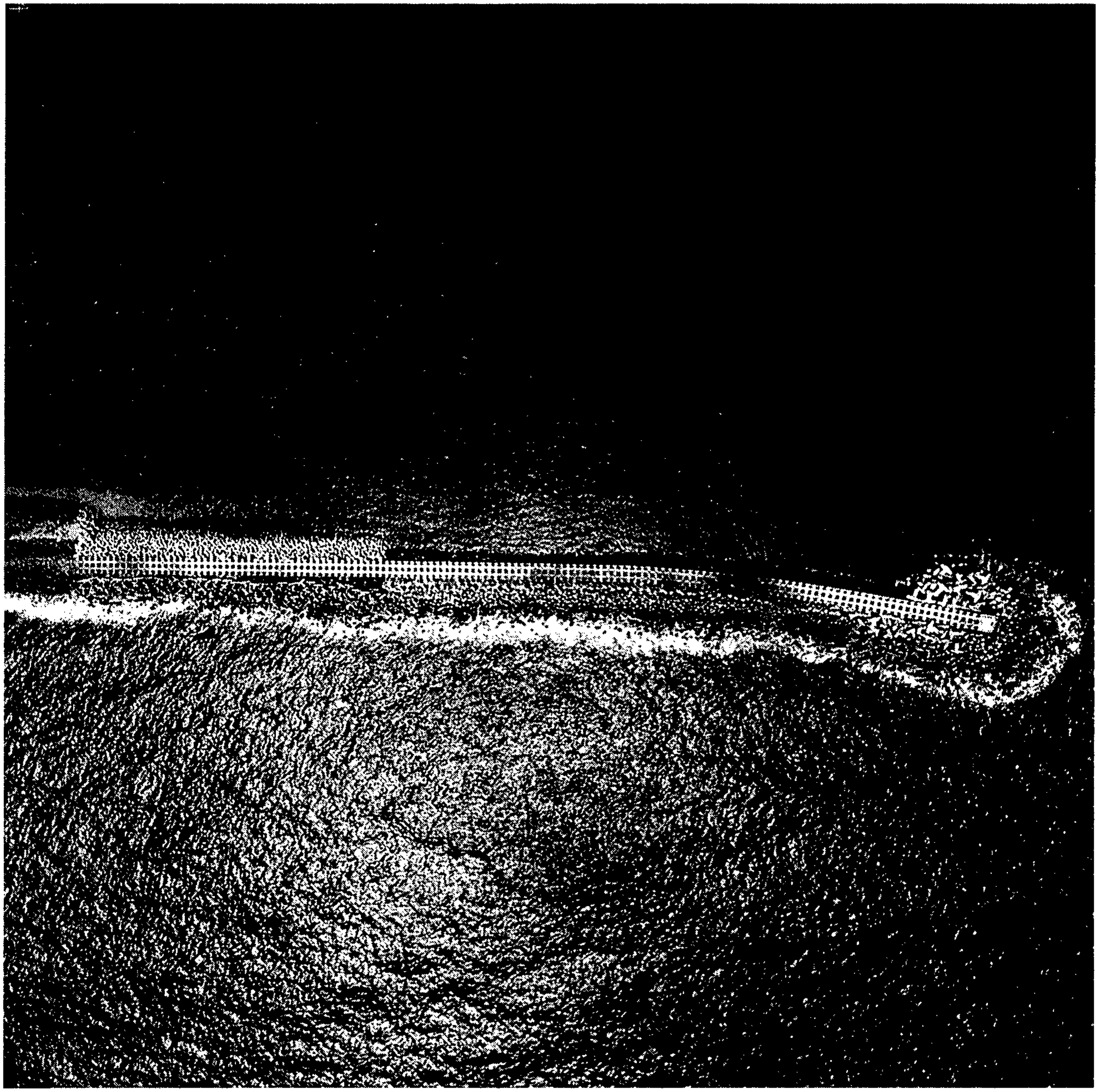

Figure 14. Stereo pair photograph of Nawiliwili breakwater (middle image)

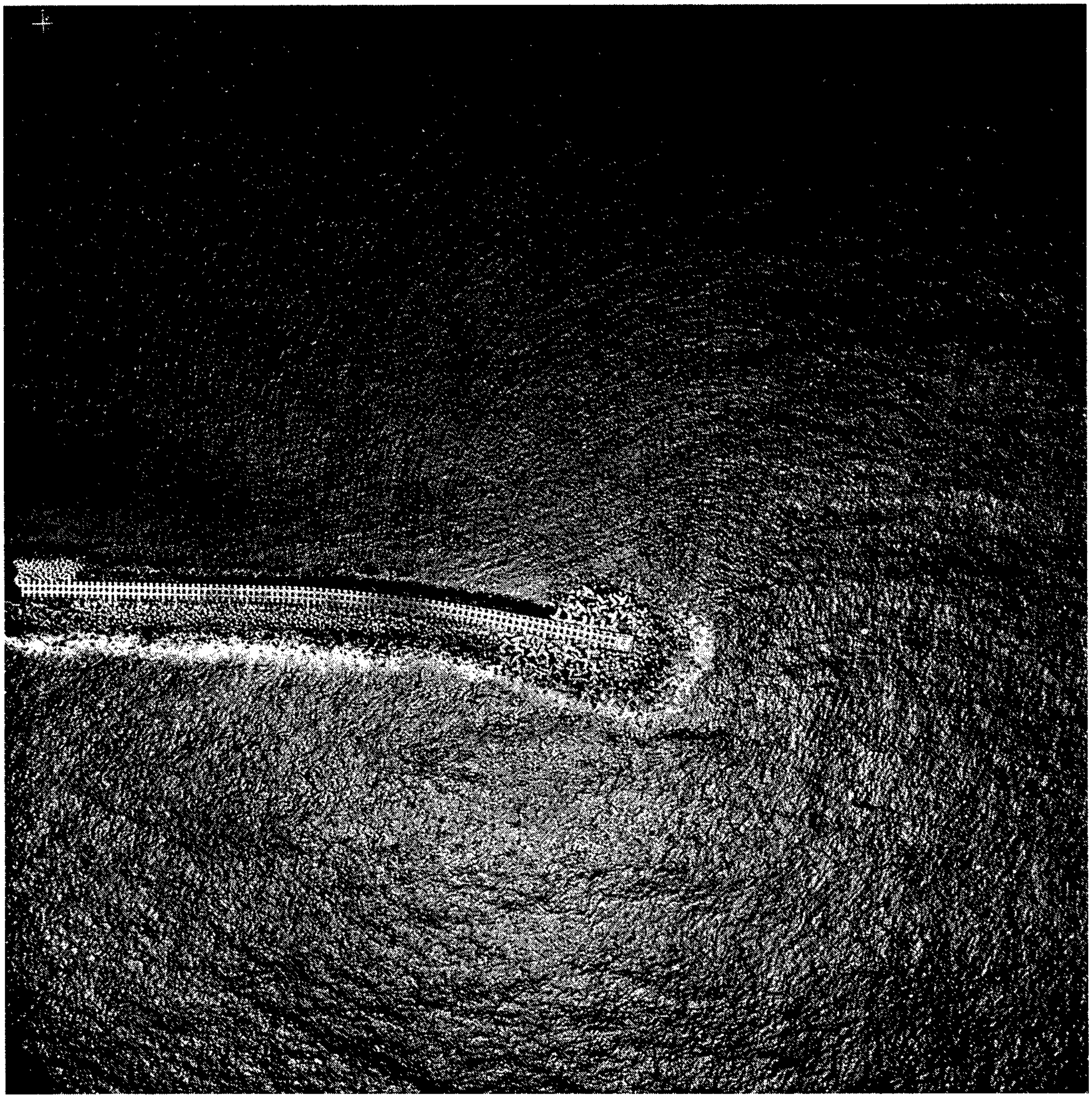

Figure 15. Stereo pair photograph of Nawiliwili breakwater (outermost image)

Photogrammetric Analysis of Armor Unit Targets

When aerial photography is planned and conducted so that each photo image overlaps the next by 60 percent or more, the two photographs comprising the overlap area can be positioned under an instrument called a stereoscope, and viewed in extremely sharp three-dimensional detail. If properly selected survey points on the ground have previously been targeted and are visible in the overlapping photography, accurate measurements of any point appearing in the photographs can be obtained. This technique is called photogrammetry.

The stereo pair images obtained during aerial photography at Nawiliwili Harbor were viewed in a Zeiss P-3 analytical stereoplotter, and stereomodels were oriented to the ground control point data previously obtained. In the stereomodel, accurate horizontal and vertical measurements can be made of any point on any armor unit appearing in the print. The stereomodel was used for all photogrammetric compilation and the development of photo maps. To establish the accuracy of the photogrammetric work, comparisons of the coordinates for selected targets obtained during the ground survey with those of the aerial survey (stereomodel) were conducted and indicated close agreement. Maximum differences were 0.076 and 0.073 m (0.25 and 0.24 ft), respectively, for the horizontal and vertical positions. An average of all horizontal and vertical positions indicated differences of less than 0.021 m (0.07 ft) and 0.018 m (0.06 ft), respectively.

A photogrammetric analysis of the armor unit targets was conducted and x, y, and z (easting, northing, and el) coordinates were obtained. Data obtained during the current (2001) survey were compared to that obtained during the aerial survey of September 1995. Comparisons of the aerial survey data for the 2001 and 1995 surveys are presented in Table 2. The table shows close comparison between two surveys indicating minimal horizontal and vertical movement of the targeted concrete armor units. Maximum movement in the horizontal and vertical directions was 0.013 m (0.42 ft) and 0.137 m (0.45 ft), respectively. The average movement of all horizontal and vertical targets, respectively, was 0.03 m (0.1 ft) and 0.046 m (0.15 ft). In general, the vertical movement of targets was slightly greater than the horizontal movements. Seventy-five percent of all vertical target movement, and 90 percent of horizontal target movement, were within 0.061 m (0.2 ft).

Table 2
Comparison of 2001 and 1995 Aerial Survey Data Obtained for Armor Unit Targets

	2001 Aerial Survey			1995 Aerial Survey			Absolute Value of Differences Between 2001 and 1995 Aerial Surveys		
Target ID	Easting (E01)	Northing (N01)	Elevation (El01), m (ft)	Easting (E95)	Northing (N95)	Elevation (El95), m (ft)	E01-E95, cm (ft)	N01-N95, cm (ft)	El01-El95, cm (ft)
NA1	550021.16	44054.24	+3.31 (+10.85)	550021.14	44054.23	+3.34 (+10.97)	0.61 (0.02)	0.30 (0.01)	3.66 (0.12)
NA2	550016.66	44048.90	+3.45 (+11.33)	550016.56	44048.92	+3.48 (+11.43)	3.04 (0.10)	0.61 (0.02)	3.0 (0.10)
NA3	550024.51	44047.06	+4.29 (+14.10)	550024.32	44047.25	+4.36 (+14.30)	5.79 (0.19)	6.40 (0.21)	6.10 (0.20)
NB1	550089.09	44168.89	+3.57 (+11.71)	550089.01	44168.83	+3.53 (+11.58)	2.44 (0.08)	1.83 (0.06)	3.96 (0.13)
NB2	550087.44	44163.06	+3.28 (+10.77)	550087.38	44163.11	+3.26 (+10.71)	1.83 (0.06)	1.52 (0.05)	1.83 (0.06)
NB3	550095.15	44163.26	+4.06 (+13.31)	550095.15	44163.26	+4.01 (+13.15)	0.00 (0.00)	0.00 (0.00)	4.88 (0.16)
NC1	550152.47	44323.32	+3.86 (+12.65)	550152.42	44323.28	+3.86 (+12.66)	1.52 (0.05)	1.22 (0.04)	0.30 (0.01)
NC2	550151.24	44316.35	+3.74 (+12.26)	550151.18	44316.22	+3.72 (+12.19)	1.83 (0.06)	3.96 (0.13)	2.13 (0.07)
NC3	550157.75	44319.23	+3.26 (+10.70)	550157.72	44319.23	+3.25 (+10.65)	0.91 (0.03)	0.00 (0.00)	1.52 (0.05)

(Sheet 1 of 3)

Table 2 (Continued)									
	2001 Aerial Survey			1995 Aerial Survey			Absolute Value of Differences Between 2001 and 1995 Aerial Surveys		
Target ID	Easting (E01)	Northing (N01)	Elevation (El01), m (ft)	Easting (E95)	Northing (N95)	Elevation (El95), m (ft)	E01-E95, cm (ft)	N01-N95, cm (ft)	El01-El95, cm (ft)
ND1	550278.00	44562.25	+2.90 (+9.51)	550278.02	44561.87	+2.93 (+9.62)	0.61 (0.02)	11.58 (0.38)	3.35 (0.11)
ND2	550277.27	44554.87	+3.12 (+10.23)	550277.28	44555.04	+3.12 (+10.25)	0.30 (0.01)	5.18 (0.17)	0.61 (0.02)
ND3	550283.39	44558.28	+4.35 (+14.28)	550283.50	44558.33	+4.34 (+14.23)	3.35 (0.11)	1.52 (0.05)	1.52 (0.05)
NE1	550304.08	44596.89	+2.80 (+9.20)	550304.08	44597.03	+2.80 (+9.19)	0.00 (0.00)	4.27 (0.14)	0.30 (0.01)
NE2	550300.84	44591.84	+2.80 (+9.19)	550300.94	44592.02	+2.78 (+9.12)	0.30 (0.10)	5.49 (0.18)	2.13 (0.07)
NE3	550297.89	44597.62	+4.39 (+14.39)	550297.98	44597.79	+4.34 (+14.24)	2.74 (0.09)	5.18 (0.17)	4.57 (0.15)
NF1	550329.28	44633.66	+3.72 (+12.23)	550329.30	44633.86	+3.76 (+12.34)	0.61 (0.02)	6.10 (0.20)	3.35 (0.11)
NF2	550331.62	44626.32	+3.70 (+12.14)	550331.67	44626.53	+3.70 (+12.14)	1.52 (0.05)	6.40 (0.21)	0.00 (0.00)
NF3	550338.22	44630.68	+5.43 (+17.82)	550338.26	44631.03	+5.48 (+17.98)	1.22 (0.04)	10.67 (0.35)	4.88 (0.16)
NG1	550358.00	44649.49	+3.93 (+12.91)	550357.90	44649.91	+4.01 (+13.18)	3.04 (0.10)	12.80 (0.42)	8.23 (0.27)
NG2	550352.29	44655.01	+3.75 (+12.31)	550352.20	44655.22	+3.77 (+12.37)	2.74 (0.09)	6.40 (0.21)	1.83 (0.06)
NG3	550347.90	44646.59	+4.67 (+15.32)	550347.86	44646.92	+4.68 (+15.34)	1.22 (0.04)	10.06 (0.33)	0.61 (0.02)
NH1	550366.29	44672.50	+3.67 (+12.03)	550366.18	44672.70	+3.69 (+12.09)	3.35 (0.11)	6.10 (0.20)	1.83 (0.06)
NH2	550367.77	44682.12	+3.70 (+12.14)	550367.81	44682.19	+3.76 (+12.32)	1.22 (0.04)	2.13 (0.07)	5.49 (0.18)
NH3	550358.64	44679.34	+4.96 (+16.27)	550358.54	44679.50	+4.98 (+16.34)	3.05 (0.10)	4.88 (0.16)	2.13 (0.07)
NJ1	550378.09	44691.29	+4.20 (+13.78)	550378.04	44691.40	+4.19 (+13.76)	1.52 (0.05)	3.35 (0.11)	0.61 (0.02)
NJ2	550371.05	44689.40	+3.66 (+12.01)	550371.11	44689.50	+3.64 (+11.94)	1.83 (0.06)	3.05 (0.10)	2.13 (0.07)
NJ3	550374.23	44681.47	+5.12 (+16.80)	550374.18	44681.69	+5.13 (+16.84)	1.52 (0.05)	6.71 (0.22)	1.22 (0.04)
NK1	550385.38	44713.19	+4.04 (+13.26)	550385.27	44713.28	+3.97 (+13.03)	3.35 (0.11)	2.74 (0.09)	7.01 (0.23)
NK2	550384.23	44705.94	+3.73 (+12.25)	550384.11	44706.02	+3.72 (+12.22)	3.66 (0.12)	2.44 (0.08)	0.91 (0.03)
NK3	550390.31	44708.51	+4.26 (+13.96)	550390.16	44708.73	+4.20 (+13.77)	4.57 (0.15)	6.71 (0.22)	5.79 (0.19)
NL1	550388.70	44733.50	+3.00 (+9.84)	550388.60	44733.48	+2.95 (+9.67)	3.05 (0.10)	0.61 (0.02)	5.18 (0.17)
NL2	550385.06	44728.24	+3.50 (+11.47)	550384.88	44728.04	+3.42 (+11.22)	5.49 (0.18)	6.10 (0.20)	7.62 (0.25)
NL3	550391.67	44727.16	+2.83 (+9.27)	550391.58	44727.08	+2.72 (+8.93)	2.74 (0.09)	2.44 (0.08)	10.36 (0.34)
NM1	550370.75	44741.59	+3.17 (+10.39)	550370.62	44741.58	+3.10 (+10.18)	3.96 (0.13)	0.30 (0.01)	6.40 (0.21)
NM2	550370.67	44748.14	+3.03 (+9.94)	550370.54	44748.12	+2.95 (+9.68)	3.96 (0.13)	0.61 (0.02)	7.92 (0.26)
NM3	550364.67	44745.57	+3.41 (+11.20)	550364.55	44745.62	+3.34 (+10.96)	3.66 (0.12)	1.52 (0.05)	7.32 (0.24)
									(Sheet 2 of 3)

Table 2 (Concluded)

Target ID	2001 Aerial Survey			1995 Aerial Survey			Absolute Value of Differences Between 2001 and 1995 Aerial Surveys		
	Easting (E01)	Northing (N01)	Elevation (El01), m (ft)	Easting (E95)	Northing (N95)	Elevation (El95), m (ft)	E01-E95, cm (ft)	N01-N95, cm (ft)	El01-El95, cm (ft)
NN1	550360.85	44751.00	+3.31 (+10.86)	550360.71	44750.96	+3.24 (+10.63)	4.27 (0.14)	1.22 (0.04)	7.01 (0.23)
NN2	550360.53	44758.03	+3.19 (+10.47)	550360.47	44757.96	+3.14 (+10.29)	1.83 (0.06)	2.13 (0.07)	5.49 (0.18)
NN3	550355.02	44754.28	+2.88 (+9.45)	550354.97	44754.32	+2.74 (+9.00)	1.52 (0.05)	1.22 (0.04)	13.72 (0.45)
NO1	550323.69	44737.82	+3.55 (+11.64)	550323.69	44737.91	+3.45 (+11.32)	0.00 (0.00)	2.74 (0.09)	9.75 (0.32)
NO2	550319.23	44745.38	+3.24 (+10.63)	550319.28	44745.39	+3.13 (+10.28)	1.52 (0.05)	0.30 (0.01)	10.67 (0.35)
NO3	550313.90	44736.50	+4.27 (+14.00)	550313.88	44736.52	+4.16 (+13.65)	0.61 (0.02)	0.61 (0.02)	10.67 (0.35)
NP1	550379.51	44744.07	+2.40 (+7.86)	550379.44	44744.10	+2.33 (+7.66)	2.13 (0.07)	0.91 (0.03)	6.10 (0.20)
NP2	550385.77	44746.65	+2.76 (+9.06)	550385.44	44746.98	+2.72 (+8.92)	10.06 (0.33)	10.06 (0.33)	4.27 (0.14)
NP3	550379.97	44749.93	+3.42 (+11.21)	550379.82	44749.87	+3.34 (+10.96)	4.57 (0.15)	1.83 (0.06)	7.62 (0.25)
NQ1	550210.15	44456.30	+4.62 (+15.17)	550210.04	44456.21	+4.51 (+14.80)	3.35 (0.11)	2.74 (0.09)	11.28 (0.37)
NQ2	550211.75	44449.92	+4.36 (+14.32)	550211.70	44449.96	+4.23 (+13.88)	1.52 (0.05)	1.22 (0.04)	13.41 (0.44)
NQ3	550216.31	44454.87	+3.71 (+12.17)	550216.27	44454.79	+3.64 (+11.95)	1.22 (0.04)	2.44 (0.08)	6.71 (0.22)
NR1	550254.91	44509.00	+2.83 (+9.28)	550254.92	44509.19	+2.79 (+9.14)	0.03 (0.01)	5.79 (0.19)	4.27 (0.14)
NR2	550255.82	44502.06	+2.33 (+7.64)	550255.79	44502.13	+2.29 (+7.52)	0.91 (0.03)	2.13 (0.07)	3.66 (0.12)
NR3	550261.04	44505.08	+4.09 (+13.43)	550261.06	44505.26	+4.10 (+13.45)	0.61 (0.02)	5.49 (0.18)	0.61 (0.02)
NS1	550120.42	44247.05	+3.28 (+10.76)	550120.35	44246.92	+3.23 (+10.61)	2.13 (0.07)	3.96 (0.13)	4.57 (0.15)
NS2	550121.56	44241.18	+3.21 (+10.52)	550121.49	44240.99	+3.17 (+10.40)	2.13 (0.07)	5.79 (0.19)	3.66 (0.12)
NS3	550126.10	44244.01	+4.90 (+16.07)	550125.93	44243.85	+4.87 (+15.98)	5.18 (0.17)	4.88 (0.16)	2.74 (0.09)
NT1	550097.83	44175.42	+2.96 (+9.70)	550097.79	44175.38	+2.92 (+9.59)	1.22 (0.04)	1.22 (0.04)	3.35 (0.11)
NT2	550100.51	44168.59	+2.80 (+9.18)	550100.50	44168.66	+2.76 (+9.06)	0.30 (0.01)	2.13 (0.07)	3.66 (0.12)
NT3	550104.23	44174.00	+4.40 (+14.44)	550104.14	44173.91	+4.35 (+14.27)	2.74 (0.09)	2.74 (0.09)	5.18 (0.17)
NV1	550034.99	44069.62	+2.75 (+9.03)	550034.92	44069.59	+2.77 (+9.10)	2.13 (0.07)	0.91 (0.03)	2.13 (0.07)
NV2	550029.99	44067.40	+2.62 (+8.60)	550029.89	44067.34	+2.63 (+8.64)	3.05 (0.10)	1.83 (0.06)	1.22 (0.04)
NV3	550033.76	44062.66	+4.21 (+13.81)	550033.67	44062.54	+4.22 (+13.86)	2.74 (0.09)	3.66 (0.12)	1.52 (0.05)
NZ1	550004.63	44017.18	+3.26 (+10.68)	550004.57	44017.18	+3.30 (+10.84)	1.83 (0.06)	0.00 (0.00)	4.88 (0.16)
NZ2	550001.19	44010.18	+3.22 (+10.56)	550001.03	44010.16	+3.23 (+10.61)	4.88 (0.16)	0.61 (0.02)	1.52 (0.05)
NZ3	550007.65	44011.41	+4.89 (+16.04)	550007.50	44011.40	+4.91 (+16.11)	4.57 (0.15)	0.30 (0.01)	2.13 (0.07)

(Sheet 3 of 3)

With the x, y, and z (easting, northing, and el) coordinates defined for each target on the various armor units, the coordinates of the centroid (center of mass) of each targeted armor unit were computed for the 2001 aerial survey. In addition, the position of each armor unit relative to the x, y, and z axes was determined. Figure 16 shows, in 3-D, the orientation of representative armor units to the three axes. The centroid coordinates of each targeted armor unit and each unit's orientation (rotation angle relative to the x, y, and z axes) are presented in Tables 3 and 4, respectively, and compared with the aerial survey results of 1995. Maximum movement of the centroids was 0.104 m (0.34 ft) and 0.113 m (0.37 ft) in the horizontal and vertical directions, respectively, while average movements were 0.027 m (0.09 ft) and 0.043 m (0.14 ft) in the horizontal and vertical directions. Changes in the rotation angle of the armor units varied from 0.0 to 10.2 deg with an average of 0.8 deg. These data indicate minimal movement of the targeted armor unit centroids.

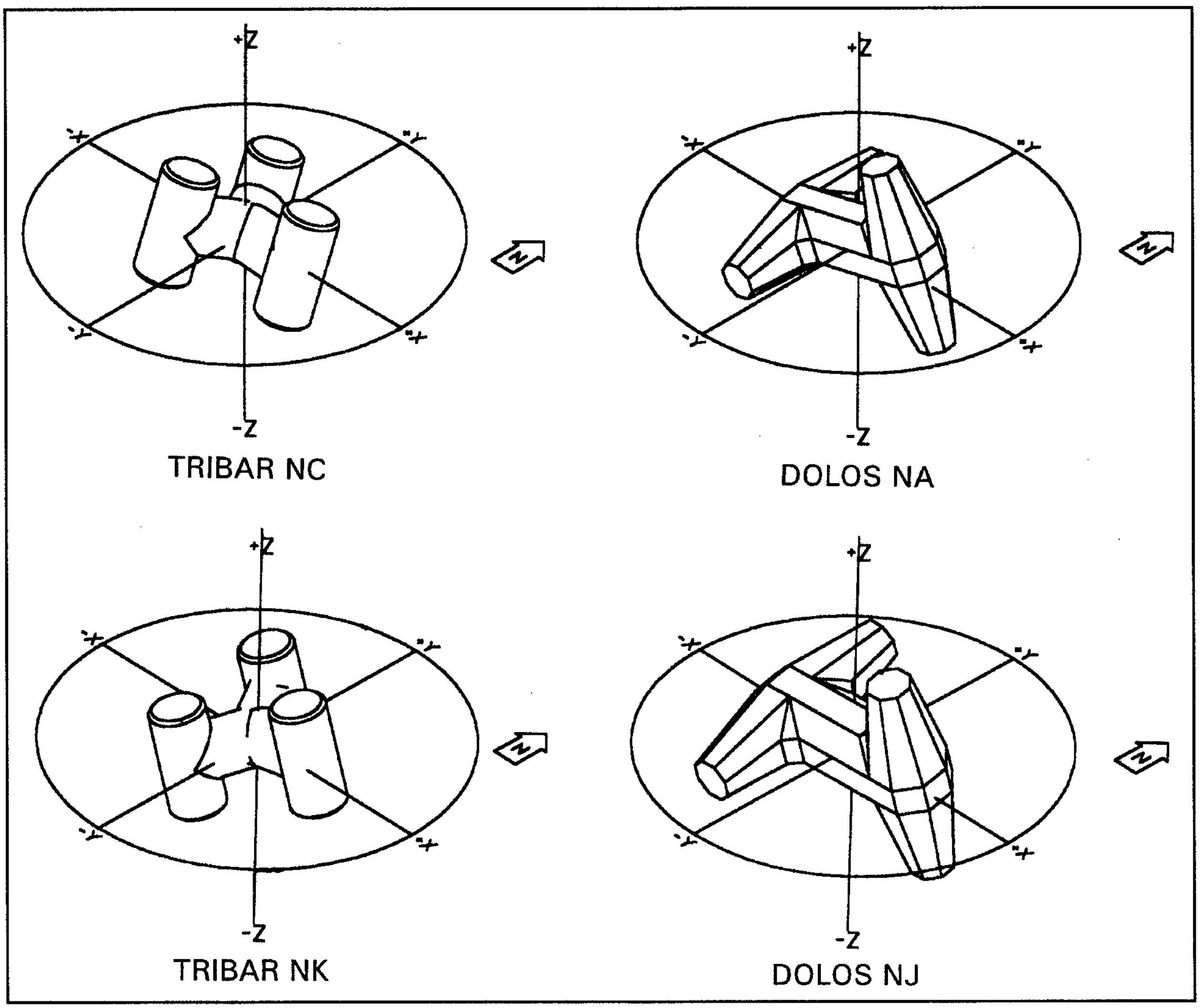

Figure 16. Representative targeted armor unit positions relative to x, y, and z axes

Table 3
Comparison of Centroid Data for Targeted Armor Units for 2001 and 1995 Aerial Survey Data

	2001 Aerial Survey			1995 Aerial Survey			Absolute Value of Differences Between 2001 and 1995 Aerial Surveys		
Armor Unit ID	Easting (E01)	Northing (N01)	Elevation (El01), m (ft)	Easting (E95)	Northing (N95)	Elevation (El95), m (ft)	E01-E95, cm (ft)	N01-N95, cm (ft)	El01-El95, cm (ft)
NA	550021.34	44049.43	2.95 (9.68)	550021.28	44049.47	3.00 (9.83)	1.83 (0.06)	1.22 (0.04)	4.57 (0.15)
NB	550091.00	44165.02	2.89 (9.47)	550090.92	44165.00	2.85 (9.35)	2.44 (0.08)	0.61 (0.02)	3.66 (0.12)
NC	550152.81	44319.92	2.66 (8.73)	550152.76	44319.89	2.65 (8.70)	1.52 (0.05)	0.91 (0.03)	0.91 (0.03)
ND	550281.03	44558.09	2.80 (9.18)	550281.04	44558.08	2.80 (9.18)	0.30 (0.01)	0.30 (0.01)	0.00 (0.00)
NE	550299.68	44596.54	2.62 (8.91)	550299.78	44596.72	2.69 (8.83)	3.05 (0.10)	5.49 (0.18)	2.44 (0.08)
NF	550334.85	44629.91	3.46 (11.34)	550334.91	44630.25	3.48 (11.43)	1.83 (0.06)	10.36 (0.34)	2.74 (0.09)
NG	550351.84	44650.13	3.13 (10.28)	550351.84	44650.40	3.16 (10.38)	0.00 (0.00)	8.23 (0.27)	3.05 (0.10)
NH	550363.04	44678.56	3.20 (10.51)	550363.02	44678.74	3.23 (10.61)	0.61 (0.02)	5.49 (0.18)	3.05 (0.10)
NJ	550374.33	44685.99	3.38 (11.09)	550374.35	44686.09	3.38 (11.09)	0.61 (0.02)	3.05 (0.10)	0.00 (0.00)
NK	550387.21	44709.49	3.02 (9.90)	550387.03	44709.53	2.97 (9.74)	5.49 (0.18)	1.22 (0.04)	4.88 (0.16)
NL	550387.71	44729.07	2.13 (6.99)	550387.58	44729.04	2.05 (6.72)	3.96 (0.13)	0.91 (0.03)	8.23 (0.27)
NM	550368.19	44745.15	2.20 (7.23)	550368.05	44745.14	2.13 (6.99)	4.27 (0.14)	0.30 (0.01)	7.32 (0.24)
NN	550358.88	44754.24	2.10 (6.90)	550358.94	44754.25	2.02 (6.62)	1.83 (0.06)	0.30 (0.01)	8.53 (0.28)
NO	550318.55	44739.02	2.74 (8.99)	550318.58	44739.05	2.64 (8.65)	0.91 (0.03)	0.91 (0.03)	10.36 (0.34)
NP	550381.71	44748.09	1.91 (6.27)	550381.49	44748.19	1.85 (6.08)	6.71 (0.22)	3.05 (0.10)	5.79 (0.19)
NQ	550211.36	44453.75	3.31 (10.87)	550211.38	44453.75	3.20 (10.50)	0.61 (0.02)	0.00 (0.00)	11.28 (0.37)
NR	550259.08	44506.35	2.35 (7.72)	550259.11	44506.48	2.33 (7.66)	0.91 (0.03)	3.96 (0.13)	1.83 (0.06)
NS	550124.54	44244.07	3.22 (10.55)	550124.46	44243.90	3.19 (10.46)	2.44 (0.08)	5.18 (0.17)	2.74 (0.09)
NT	550102.30	44173.37	2.79 (9.15)	550102.26	44173.35	2.75 (9.03)	1.22 (0.04)	0.61 (0.02)	3.66 (0.12)
NV	550033.60	44065.05	2.53 (8.31)	550033.52	44065.00	2.55 (8.35)	2.44 (0.08)	1.52 (0.05)	1.22 (0.04)
NZ	550006.06	44012.15	3.22 (10.57)	550005.95	44012.17	3.25 (10.66)	3.35 (0.11)	0.61 (0.02)	2.74 (0.09)

Table 4
Comparison of Rotation Angles for Targeted Armor Units for 2001 and 1995 Aerial Survey Data

Armor Unit ID	2001 Rotation Angle (deg)			1995 Rotation Angle (deg)			Difference Between 2001 and 1995 Rotation Angles (deg)		
	X axis	Y axis	Z axis	X axis	Y axis	Z axis	X axis	Y axis	Z axis
NA	7.0	4.0	48.8	5.7	3.8	49.2	1.3	0.2	-0.4
NB	13.0	-9.4	74.8	13.6	-8.8	64.6	-0.6	-0.6	10.2
NC	-4.8	16.4	-37.1	-4.3	16.8	-36.6	-0.5	-0.4	-0.5
ND	-8.4	4.5	83.9	-7.3	4.3	85.0	-1.2	0.2	-1.1
NE	-13.8	-1.5	-120.8	-13.3	-0.9	-121.1	-0.5	-0.6	0.3
NF	-5.9	-3.1	107.9	-6.5	-3.9	109.0	0.6	0.8	-1.1
NG	12.9	-4.8	-44.9	13.3	-6.4	-43.9	-0.4	1.6	-1.0
NH	4.2	-0.8	-98.8	4.7	0.0	-99.5	-0.5	-0.8	0.7
NJ	4.0	-13.0	12.3	3.1	-13.6	12.3	0.9	0.6	0.0
NK	12.8	-5.9	-39.4	11.1	-6.3	-38.7	1.7	0.4	-0.7
NL	-18.8	4.7	-64.8	-18.4	6.0	-63.7	-0.4	-1.3	-1.1
NM	0.8	10.9	25.9	0.4	11.2	25.7	0.4	-0.2	0.1
NN	-8.6	-8.7	31.7	-9.3	-11.1	30.8	0.7	2.4	0.9
NO	12.5	-3.6	-60.7	12.8	-3.9	-60.5	-0.3	0.3	-0.2
NP	21.3	18.2	-40.3	21.5	18.2	-38.2	-0.2	0.0	-2.1
NQ	-4.4	25.3	-11.5	-3.3	24.0	-11.5	-1.1	1.3	0.0
NR	-12.3	-13.9	95.6	-12.9	-13.4	95.5	0.6	-0.5	0.1
NS	-16.6	-6.9	99.5	-17.4	-6.6	99.6	0.8	-0.3	-0.1
NT	-10.9	-4.4	112.3	-11.2	-4.6	112.1	0.3	0.2	0.2
NV	-11.8	-12.8	20.3	-11.4	-13.1	20.3	-0.4	0.3	0.0
NZ	-14.5	-2.7	64.0	-14.4	-3.5	64.0	-0.1	0.8	0.0

Photo maps combine the image characteristics of a photograph with the geometric qualities of a map. The image is rectified and free from skewness and distortion, and therefore, precise horizontal measurements may be obtained using an engineer scale. Photo maps were prepared for the outer 260-m (850-ft) length of the Nawiliwili breakwater for the 2001 survey. They were produced on Mylar sheets at a scale of 1:240. An example of a photo map of the head of the Nawiliwili breakwater is shown in Figure 17. In an effort to quantify movement of nontargeted concrete armor units, photo maps obtained for the 1995 and 2001 surveys were compared. It appeared that negligible movement of nontargeted units had occurred between the surveys.

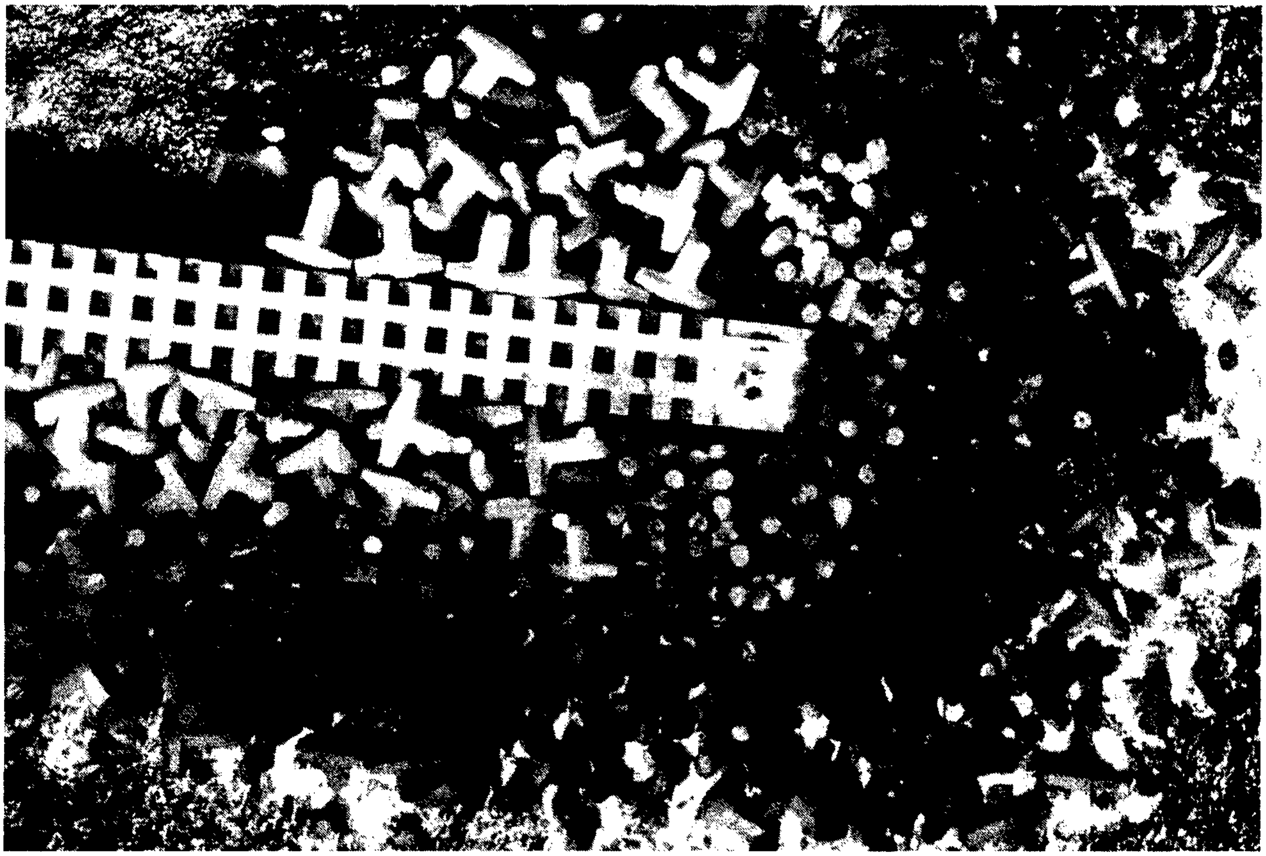

Figure 17. Photo map of head of Nawiliwili breakwater

In summary, detailed and accurate information relative to the armor unit positions for the Nawiliwili Harbor breakwater have been captured by means of aerial photography and photogrammetric analysis. Comparisons of 2001 target data to that obtained previously in 1995 indicated horizontal movements ranging from 0.0 to 0.013 m (0.0 to 0.42 ft) and vertical movements ranging from 0.0 to 0.137 m (0.0 to 0.45 ft). Additional comparisons of 2001 centroid data to that of 1995 revealed horizontal movements ranging from 0.0 to 0.104 m (0.0 to 0.34) and vertical movements ranging from 0.0 to 0.113 m (0.0 to 0.37 ft). These data indicate that negligible movement of the targeted concrete armor units occurred between 1995 and 2001. Additionally, comparison of nontargeted armor units on the rectified photo maps indicated negligible movement.

Full-scale hard copies of aerial photographs and photo maps are on file at the authors' offices at CHL and the Honolulu District. In addition, all photogrammetric compilations and analyses have been stored on diskettes in MICROSTATION files for future use. Data are stored and can be retrieved and compared against data obtained during subsequent monitoring. Thus, armor unit movement may continue to be quantified precisely in future years.

Broken Armor Unit Survey

On 20 August 2001, a survey of broken/cracked armor units above the waterline was conducted on the outer 260-m (850-ft) portion of the Nawiliwili Harbor breakwater. During the inspection, each broken armor unit was identified and photographed, and its approximate location relative to breakwater station and distance from a baseline was recorded. The baseline was the approximate center line of the structure. A total of 77 broken or cracked armor units was identified along the structure during the walking survey.

The approximate locations of broken/cracked armor units along the outer portion of the breakwater are shown in Figure 18, and detailed data obtained during the broken armor unit inventory are shown in Table 5. Armor unit numbers identified in Figure 18 correspond to those listed in Table 5. As shown, broken units occur along the entire length on the sea side of the structure, but in general, are more concentrated along the seaward end of the breakwater. Fifty-seven percent of the broken units are located on the outer half of the structure, and 27 percent of the broken units are situated on the outer 45.7-m (150-ft) length of the breakwater (sta 19+00 - 20-50). With regard to distance from baseline, the majority of broken units (71 percent) are located between 7.6 and 18.3 m (25 and 60 ft) seaward of the baseline. These units are in the active wave zone.

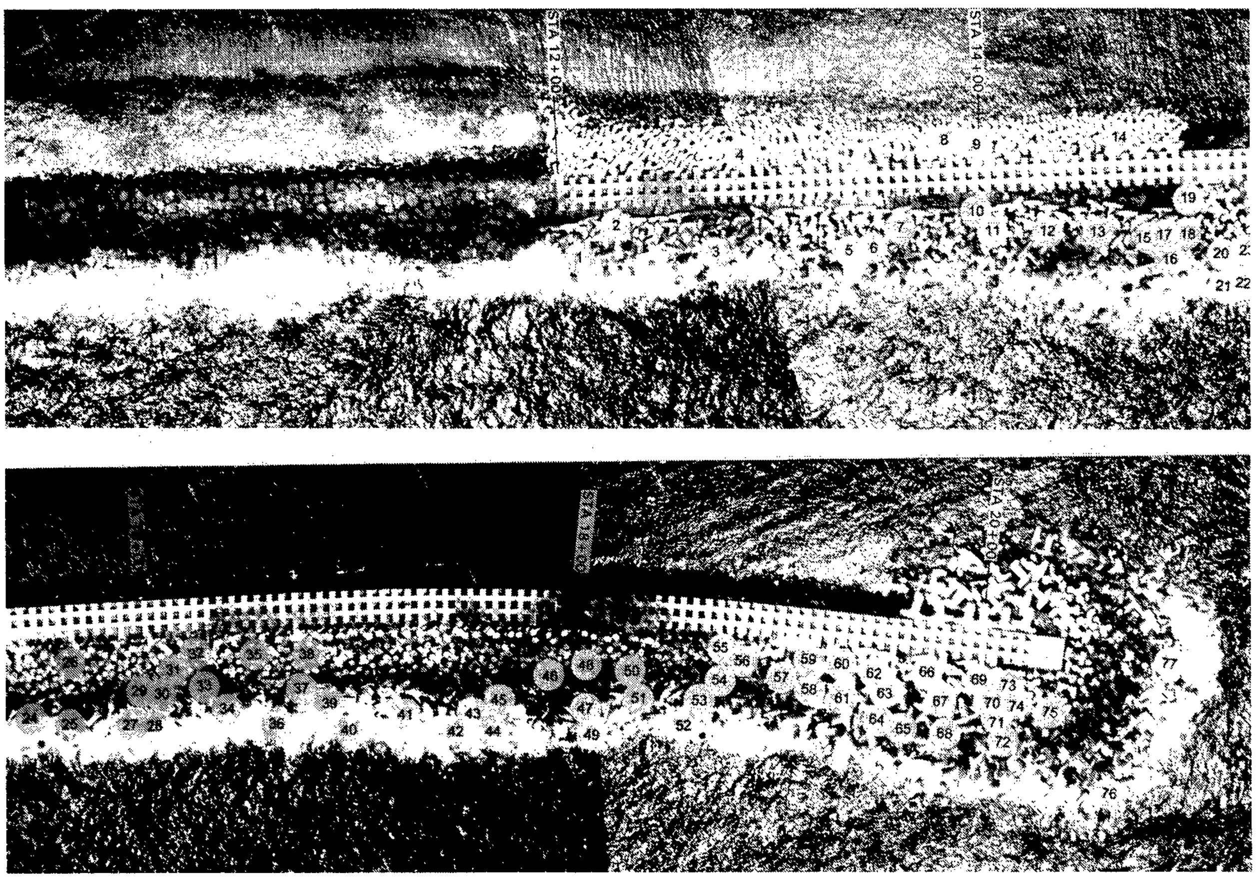

Figure 18. Approximate locations of broken/cracked armor units along outer portion of Nawiliwili Harbor breakwater

Table 5
Broken Armor Unit Inventory Data

Armor Unit No.	Station No.	Type of Armor Unit	Offset from Center line, m (ft)		Type of Break, Comments
			Sea side	Harbor side	
1	12+10	9,980-kg (11-ton) Dolos	9.45 (31)		Straight shank-fluke break
2	12+27	9,980-kg (11-ton) Dolos	4.57 (15)		Straight mid-shank break
3	12+73	9,980-kg (11-ton) Dolos	9.45 (31)		Straight shank-fluke break
4	12+88	5,900-kg (6.5-ton) Tribar		3.66 (12)	Leg broken off through center of unit
5	13+40	9,980-kg (11-ton) Dolos	10.36 (34)		Angled fluke-shank break
6	13+49	9,980-kg (11-ton) Dolos	10.36 (34)		Straight mid-shank break
7	13+60	9,980-kg (11-ton) Dolos	7.62 (25)		Straight fluke-shank break
8	13+87	5,900-kg (6.5-ton) Tribar		3.66 (12)	Leg broken off – placed as two-leg unit
9	13+98	5,900-kg (6.5-ton) Tribar		3.66 (12)	Leg broken off – placed as two-leg unit
10	14+02	9,980-kg (11-ton) Dolos	6.10 (20)		Angled mid-shank break
11	14+04	9,980-kg (11-ton) Dolos	7.62 (25)		Straight mid-shank break
12	14+34	9,980-kg (11-ton) Dolos	8.53 (28)		Straight shank-fluke break
13	14+53	9,980-kg (11-ton) Dolos	8.23 (27)		Angled mid-shank break
14	14+69	5,900-kg (6.5-ton) Tribar		3.66 (12)	Leg broken off – placed as two-leg unit
15	14+84	9,980-kg (11-ton) Dolos	10.06 (33)		Straight mid-shank break
16	14+88	9,980-kg (11-ton) Dolos	11.28 (37)		Straight shank-fluke break
17	14+89	9,980-kg (11-ton) Dolos	10.06 (33)		Straight mid-shank break
18	14+93	9,980-kg (11-ton) Dolos	10.06 (33)		Angled fluke-shank break
19	15+02	16,150-kg (17.8-ton) Tribar	6.10 (20)		Leg broken off, crack through center
20	15+15	16,150-kg (17.8-ton) Tribar	13.72 (45)		Broken through center
21	15+16	9,980-kg (11-ton) Dolos	16.15 (53)		Straight fluke-shank break
22	15+25	9,980-kg (11-ton) Dolos	16.15 (53)		Straight shank-fluke break
23	15+29	9,980-kg (11-ton) Dolos	12.19 (40)		Straight mid-shank break
24	15+42	9,980-kg (11-ton) Dolos	13.72 (45)		Straight mid-shank break
25	15+60	9,980-kg (11-ton) Dolos	14.63 (48)		Straight fluke-shank break
26	15+62	16,150-kg (17.8-ton) Tribar	6.10 (20)		Three legs separated through center
27	15+96	9,980-kg (11-ton) Dolos	15.54 (51)		Straight mid-shank break
28	15+96	9,980-kg (11-ton) Dolos	15.54 (51)		Angled shank-fluke break
29	15+98	9,980-kg (11-ton) Dolos	11.28 (37)		Straight shank-fluke break
30	16+02	9,980-kg (11-ton) Dolos	11.28 (37)		Straight mid-shank break
31	16+10	9,980-kg (11-ton) Dolos	8.53 (28)		Angled mid-shank break
32	16+18	16,150-kg (17.8-ton) Tribar	6.40 (21)		Portion of one leg broken off
33	16+23	9,980-kg (11-ton) Dolos	10.36 (34)		Straight fluke-shank break
34	16+31	9,980-kg (11-ton) Dolos	13.11 (43)		Straight fluke-shank break
35	16+50	16,150-kg (17.8-ton) Tribar	5.79 (19)		Leg broken off

(Sheet 1 of 3)

Table 5 (Continued)					
Armor Unit No.	Station No.	Type of Armor Unit	Offset from Center line, m (ft)		Type of Break, Comments
			Sea side	Harbor side	
36	16+57	9,980-kg (11-ton) Dolos	16.46 (54)		Straight mid-shank break
37	16+70	9,980-kg (11-ton) Dolos	10.67 (35)		Straight shank-fluke break
38	16+76	16,150-kg (17.8-ton) Tribar	6.40 (21)		Leg cracked near center of unit
39	16+83	9,980-kg (11-ton) Dolos	13.41 (44)		Straight mid-shank break
40	16+90	9,980-kg (11-ton) Dolos	16.46 (54)		Straight shank-fluke break
41	17+21	9,980-kg (11-ton) Dolos	15.24 (50)		Straight fluke-shank break
42	17+46	9,980-kg (11-ton) Dolos	17.07 (56)		Angled shank-fluke break
43	17+58	9,980-kg (11-ton) Dolos	15.85 (52)		Straight mid-shank break
44	17+59	9,980-kg (11-ton) Dolos	16.76 (55)		Angled shank-fluke break
45	17+62	9,980-kg (11-ton) Dolos	13.72 (45)		Straight mid-shank break
46	17+92	9,980-kg (11-ton) Dolos	9.45 (31)		Straight fluke-shank break
47	18+10	9,980-kg (11-ton) Dolos	15.24 (50)		Straight fluke-shank break
48	18+10	16,150-kg (17.8-ton) Tribar	7.92 (26)		Broken through center
49	18+12	9,980-kg (11-ton) Dolos	17.68 (58)		Angled fluke-shank break
50	18+30	9,980-kg (11-ton) Dolos	9.14 (30)		Straight fluke-shank break
51	18+35	9,980-kg (11-ton) Dolos	12.50 (41)		Straight shank-fluke break
52	18+59	9,980-kg (11-ton) Dolos	15.85 (52)		Straight mid-shank break
53	18+65	9,980-kg (11-ton) Dolos	12.19 (40)		Straight mid-shank and straight fluke-shank breaks
54	18+77	16,150-kg (17.8-ton) Tribar	8.23 (27)		Leg broken off unit
55	18+78	16,150-kg (17.8-ton) Tribar	4.88 (16)		Leg broken off unit
56	18+85	16,150-kg (17.8-ton) Tribar	5.49 (18)		Leg broken off unit
57	19+10	9,980-kg (11-ton) Dolos	8.23 (27)		Straight shank-fluke break
58	19+15	9,980-kg (11-ton) Dolos	8.84 (29)		Straight shank-fluke break
59	19+20	16,150-kg (17.8-ton) Tribar	4.27 (14)		Broken through center, all legs separated
60	19+32	16,150-kg (17.8-ton) Tribar	4.57 (15)		Leg broken off unit
61	19+34	16,150-kg (17.8-ton) Tribar	8.53 (28)		Leg broken off unit
62	19+50	20,865-kg (23-ton) Dolos	6.10 (20)		Straight mid-shank break
63	19+52	16,150-kg (17.8-ton) Tribar	8.53 (28)		Cracked through center of unit
64	19+56	20,865-kg (23-ton) Dolos	12.80 (42)		Angled mid-shank break
65	19+57	20,865-kg (23-ton) Dolos	12.50 (41)		Straight fluke-shank break
66	19+74	16,150-kg (17.8-ton) Tribar	4.27 (14)		Leg broken off unit
67	19+79	20,865-kg (23-ton) Dolos	8.53 (28)		Angled mid-shank break
68	19+82	20,865-kg (23-ton) Dolos	12.50 (41)		Straight shank-fluke break
69	20+03	16,150-kg (17.8-ton) Tribar	4.57 (15)		Two legs broken off unit
					(Sheet 2 of 3)

Table 5 (Concluded)					
Armor Unit No.	Station No.	Type of Armor Unit	Offset from Center line, m (ft)		Type of Break, Comments
			Sea side	Harbor side	
70	20+11	16,150-kg (17.8-ton) Tribar	7.32 (24)		Leg broken off unit
71	20+11	16,150-kg (17.8-ton) Tribar	9.75 (32)		Leg broken off unit
72	20+13	20,865-kg (23-ton) Dolos	13.11 (43)		Angled mid-shank break
73	20+13	16,150-kg (17.8-ton) Tribar	5.79 (19)		Leg broken off unit
74	20+16	16,150-kg (17.8-ton) Tribar	7.01 (23)		Leg broken off unit
75	20+34	16,150-kg (17.8-ton) Tribar	8.23 (27)		Leg cracked
76	20+67	20,865-kg (23-ton) Dolos	18.59 (61)		Angled shank-fluke break
77	20+90	20,865-kg (23-ton) Dolos		0.30 (1)	Straight shank-fluke crack off head

(Sheet 3 of 3)

Types of breaks for the dolosse included shank and fluke breaks. These were characterized as mid-shank, shank-fluke (shank broken in vicinity of fluke), and fluke-shank (fluke broken off at junction with shank). Also recorded were straight breaks (broken straight across) and angled breaks (broken at some angle to the dolos limb). For the tribars, types of breaks included those through the center section of the unit where one or more legs were separated from the unit, and those in which just a portion of one of the legs was broken off. Views of representative types of breaks for the armor units are shown in Figures 19-22. Armor units with hairline cracks on one side were not counted, only those that were cracked all the way through were considered a break for recording purposes.

Of the 77 broken or cracked armor units, 44 were 9,980-kg (11-ton) dolosse, 21 were 16,150-kg (17.8-ton) tribars, 8 were 20,865-kg (23-ton) dolosse, and four were 5,900-kg (6.5-ton) tribars. Considering the types of breaks, 39 percent (17 units) of the 9,980-kg (11-ton) dolosse had mid-shank breaks, 32 percent 14 (units) had shank-fluke breaks, and 29 percent (13 units) had fluke-shank breaks. Of the eight broken 20,865-kg (23-ton) dolosse, four had mid-shank breaks, three had shank-fluke breaks, and one had a fluke-shank break. Of all the dolosse breaks recorded, 75 percent were straight and 25 percent were angled. Of the 21 broken 16,150-kg (17.8-ton) tribars, 16 (76 percent) consisted of at least one leg broken off through the center of the unit. The four broken 5,900-kg (6.5-ton) tribars on the harbor side of the breakwater appeared to have been placed in that condition. They seemed to have been fitted on the crest adjacent to the rib cap.

During the previous broken armor unit survey conducted in August 1995, a total of 61 broken or cracked armor units were identified along the structure during the walking survey. Due to excessive wave action, however, broken/ cracked armor units along the water's edge may have been missed, since this portion of the structure was inaccessible by foot. In September 1995, an aerial survey of broken/cracked armor units was conducted by helicopter. This survey identified 39 broken or cracked armor units along the structure. Photographs and

locations of the damaged units were recorded. Many of these armor units were duplicates of those obtained during the walking survey. After evaluating the data from the two surveys, it was determined that 70 broken/cracked armor units existed on the structure. The helicopter survey identified nine additional units along the water's edge that were not recorded during the walking survey due to wave action.

Figure 19. Dolos with mid-shank break

Figure 20. Dolos with fluke-shank break

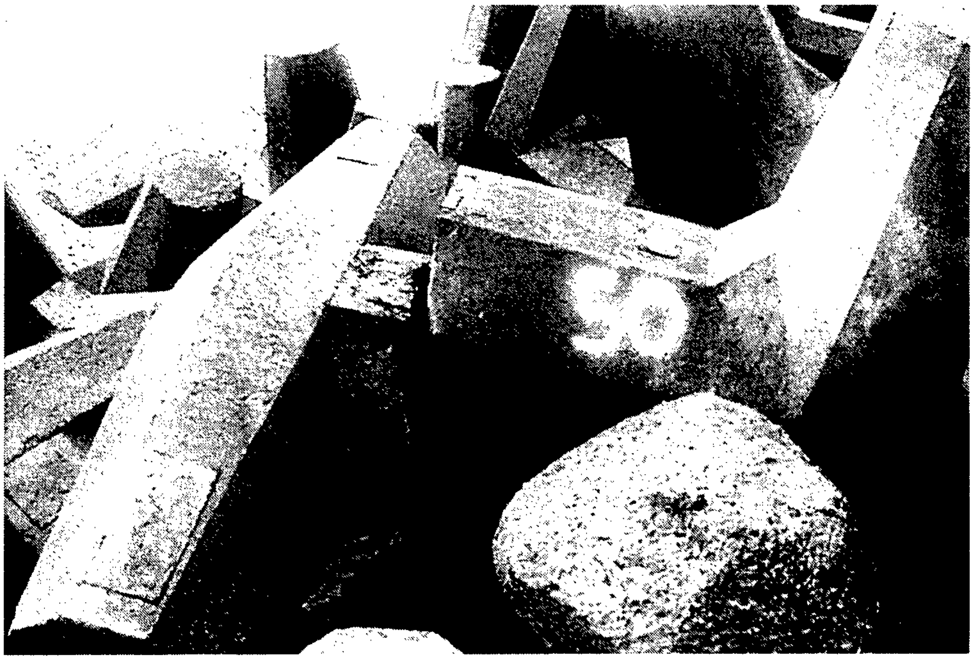

Figure 21. Dolos with shank-fluke break

Figure 22. Tribar with break through center section of unit

A comparison of the two surveys revealed 70 broken/cracked concrete armor units identified in 1995 and 77 broken/cracked units in 2001. Of the seven additional units identified in 2001, six were located along the water's edge. Since the excessive wave action in 1995 prevented a close examination of the armor units at the water's edge, they may have been overlooked. Therefore, it appears that minimal armor unit breakage occurred between 1995 and 2001.

3 Summary and Findings

The Nawiliwili Harbor breakwater has been repeatedly subjected to major storm events, including three hurricanes, during its 80-year history. As a result, extensive breakwater damage has occurred. Major rehabilitations were completed in 1959, 1977, and 1987. The structure was originally armored with keyed-and-fitted stone, but now has several sizes of tribar and dolos armor units. The Nawiliwili breakwater is one of the most complex rubble-mound structures the Corps has constructed.

Sound, quantifiable data relative to the positions of the concrete armor units were initially obtained in 1995 under the "Periodic Inspections" work unit of the MCNP Program. Data from limited ground-based surveys, aerial photography, and photogrammetric analysis were obtained to establish precise base level conditions for the Nawiliwili Harbor breakwater. Accuracy of the photogrammetric analysis was validated and defined through comparison of ground and aerial survey data on control points and targets established on the structure. A method of high resolution, stereo aerial photographs, a stereoplotter, and MICROSTATION-based software was developed to analyze the entire above-water armor unit fields and quantify armor positions and subsequent movement. A broken armor unit survey conducted during the 1995 effort resulted in a well-documented data set that could be compared to subsequent survey data.

Similar data were obtained during 2001 and compared with the 1995 data obtained previously. An analysis of these data indicated negligible movement of the concrete armor units on Nawiliwili Harbor breakwater. Maximum movement of the targets established on the concrete armor units in the horizontal and vertical directions, respectively, was 0.013 m (0.42 ft) and 0.137 m (0.45 ft); and the average movement of all horizontal and vertical targets was 0.03 m (0.1 ft) and 0.046 m (0.15 ft). Maximum movement of the targeted armor unit centroids was 0.104 m (0.34 ft) and 0.113 m (0.37 ft) in the horizontal and vertical directions, respectively, while average movements were 0.027 m (0.09 ft) and 0.043 m (0.14 ft) in the horizontal and vertical directions.

A total of 70 broken/cracked concrete armor units were identified in the 1995 survey, and 77 broken/cracked units were identified in 2001. However as reported previously, high-wave action during the 1995 walking inspection prevented a close examination of armor units at the water's edge. Of the seven additional broken units in 2001, six were located along the water's edge and may

have been overlooked in 1995 due to the excessive wave action. Therefore, it appears that minimal armor unit breakage occurred between 1995 and 2001.

The Nawiliwili Harbor breakwater will be revisited in the future under the "Periodic Inspections" work unit to gather data by which continued assessments can be made on the long-term response of the structure to its environment. The insight gathered from these efforts will allow engineering decisions to be made, based on sound data, as to whether or not closer surveillance and/or repair of the structure might be required to reduce its chances of failing catastrophically. Also, the periodic inspection methods developed and validated for this structure will be used to gain insight into other Corps structures.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
June 2002

2. REPORT TYPE
Final report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Periodic Inspection of Nawiliwili Harbor Breakwater, Kauai, Hawaii; Armor Unit Monitoring for Period 1995-2001

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Robert R. Bottin, Jr., Daniel T. Meyers

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199; U.S. Army Engineer District, Honolulu, Building 230, Fort Shafter, HI 96858-5440

8. PERFORMING ORGANIZATION REPORT NUMBER
ERDC/CHL TR-02-7

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Selected coastal navigation structures are periodically monitored under the "Periodic Inspections" work unit of the Monitoring Completed Navigation Projects Program. Such monitoring is done to gain an understanding of the long-term structural response of unique structures to their environment. Periodic data sets are used to improve knowledge in design, construction, and maintenance of both existing and proposed coastal navigation projects.

The Nawiliwili Harbor breakwater, Hawaii, was nominated for periodic monitoring by the U.S. Army Engineer District, Honolulu. The positions of the above-water, concrete armor units (tribars and dolosse) on the breakwater were initially obtained in 1995 through limited ground surveys, aerial photography, and photogrammetric analysis. An inventory of broken armor units on the breakwater also was obtained. The structures were revisited in 2001 to determine changes that had occurred. Results indicated negligible movement of the concrete armor units and minimal armor unit breakage on the breakwater.

The site will again be revisited in the future and the long-term structural response of the structure to its environment will continue to be tracked. This data set will facilitate engineering decisions concerning whether or not closer surveillance and/or repair of the breakwater might be required to reduce its chance of failing catastrophically. The periodic inspection methods developed and validated for the Nawiliwili Harbor breakwater may also be used to gain insight into other Corps structures.

15. SUBJECT TERMS

Aerial photography	Concrete armor units	Periodic inspections	Tribars
Breakwaters	Dolosse	Photogrammetry	
	Nawiliwili Harbor, Kauai, HI	Remote sensing	

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		39	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18